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RESIDUAL STRESSES IN 17-4 PH STEEL

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LESSELLS AND ASSOCIATES, INC.
303 BEAR HILL ROAD
WALTHAM, MASSACHUSETTS 02154

FOREWORD

The purpose of this report is to present the final results of an investigation of residual stresses in 17-4 PH steel and to recommend treatments for application to material used in the manufacture of strain gage balances. The study was performed by Lessells and Associates, Inc., Waltham, Massachusetts under NASA Contract NAS1-4577. The work was administered under the direction of the Instrument Research and Development Division of Langley Research Center with Mr. C. Saunders serving as project engineer for the division.

Mr. R. Brodrick was the project engineer responsible for the study, being assisted by other members of the Lessells and Associates, Inc. staff including Mr. J. Cragin, Miss G. Newton, Mr. D. Leone, Mr. F. Ranstrom, and Mr. E. Gugger.

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ABSTRACT

This report contains the results of an investigation which was performed to determine the residual stresses in 17-4 PH steel bars of various heat treatments and to evaluate the effects of these stresses on the dimensional integrity of typical strain gage balances. It is found that the as-received material contains high residual stresses but that these can be reduced by thermal treatment. An optimum sequence of thermal treatments and machining steps is recommended.

Author

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I. INTRODUCTION

The work described in the following report was undertaken in order to determine the effects of various thermal and machining sequences on the residual stresses in 17-4 PH steel. The immediate application of this information would be in the processing of strain gage balances for use in wind tunnel force measurements. It would also be of interest in other applications of this material.

In order to produce high-quality data, the strain gage balances must be held to very close dimensional tolerances. Any distortion will generally cause the balance to be of less than the highest quality and therefore of little or no value. The machining sequences required are such that some of this distortion does not appear until the final operation, after which it is impossible to correct.

One possible source of distortion lies in the residual stress patterns existing in the as-received material. These residual stresses are partially relieved during machining, this relief necessarily becoming evident as distortion of the balance.

A review of the processing given the bar stock in the steel mill revealed that the final operation could be expected to create high residual stresses. The bars are solution-treated at 1900°F in a car furnace. They become severely distorted during this treatment. After cooling the bars are cold-straightened in a Medart roller straightener. They are then centerless-ground and prepared for shipment.

The severe cold-straightening necessarily causes large amounts of plastic flow in the bars. This must certainly leave high residual stresses which can be expected to contribute to any distortion of the final machined product.

The current investigation was directed toward a recommendation of the optimum heat-treating and machining procedure which might be expected to result in a lower scrap rate and higher quality of strain gage balances.

II. TEST OUTLINE

The following four types of test were conducted. Each of the types is discussed in greater detail in succeeding sections of this report.

1. Determination of residual stresses in bar stock, utilizing the "boring-out" method. Tests were conducted on 3/4-inch and 2-inch diameter stock which had been subjected to various thermal histories.

2. Measurement of strains and deflections in a number of simulated axial-force-sensing sections typical of strain gage balance design. These were subjected to a number of thermal and machining sequences and histories.

3. Observation of the long-term stability of bar stock which had been subjected to various thermal histories. Stability was determined by comparison of periodic dimensional measurements.

4. A few simple tests were made to determine any influence of machining sequences and rates on the distortion of a typical balance cruciform section. Material of various thermal treatments was utilized.

III. TEST MATERIAL

Vacuum-melted 17-4 PH (AMS 2300A) bar stock was purchased from Armco Steel Corporation. The following analysis applies to both the 3/4-inch and 2-inch diameter stock:

Heat Number	V64152
Chromium	15.98%
Nickel	4.36
Copper	3.29
Manganese	0.17
Silicon	0.63
Carbon	0.029
Phosphorus	0.017
Sulfur	0.011
Columbium	0.25
Tantalum	0.02

Material was free of defects as determined by magnaflux and ultrasonic inspection. It was received in Condition A (1875 - 1925°F solution treatment), straightened and centerless ground.

Specimens were selected from the bars in such a manner as to distribute all portions of each bar throughout the different specimen types. That is, the first length to be cut off was designated an axial specimen, the next a boring specimen, and so forth in rotation.

IV. PROCEDURE

A. Heat Treatment

Each of the several types of test involved specimens of various heat treatments. The heat treating procedures discussed in this section apply to all of the test types, although the sequences were varied, as described in the individual test procedures.

The several heat treatments used are as described in the following paragraphs.

1. As received: This is the condition of the material as it was delivered. As described in the Introduction, the material had been solution treated at $1900 \pm 25^{\circ}F$, cold-straightened and centerless-ground.

2. Re-solution treatment with air cool: The material was heated to $1900 \pm 25^{\circ}F$ in an Argon atmosphere and held at temperature for one-half hour. It was then removed from the furnace and allowed to cool to room temperature. In the case of the simulated axial sections treated in the machined condition, the furnace was backfilled with room-temperature Argon in order to minimize scaling during cooling.

3. Anneal: This term is used synonymously with "re-solution and air cool." In this work it applies to a treatment subsequent to machining. The term "anneal" is actually a misnomer when applied to 17-4 PH steel.

4. Re-solution treatment with oil quench: The treatment in this case was the same as above except that, after time at temperature, the furnace was opened, the specimens placed in a basket and the basket immersed in oil. Although no temperature measurements were made during the transfer, the entire operation was done quickly so that the degree of air cooling prior to quenching was essentially negligible.

5. $925^{\circ}F$ precipitation harden: Specimens were heated to $925 \pm 15^{\circ}F$ in air for four hours, then air cooled. This treatment results in a hardness of approximately 42 Rockwell C, with ultimate strength of 190,000 psi, yield strength of 175,000 psi and 54% reduction of area.

6. $1075^{\circ}F$ precipitation harden: Specimens were heated to $1075 \pm 15^{\circ}F$ in air for four hours, then air cooled. This treatment gives approximately Rockwell C36 hardness, 165,000 psi ultimate

strength, 150,000 psi yield strength and 58% reduction of area. This treatment is of interest in cases where maximum strength is not required. It results in ease of machinability in the hardened condition, a desirable quality.

B. Boring Tests for Residual Stress Determination

1. Theory: Residual stress determinations were performed on the basis of the process commonly known as the "Sachs Boring-Out Method." The background of the method is covered in a number of references. Perhaps the best reference on residual stresses in general, including the Sachs Method, is a Marburg Lecture by W.M. Baldwin, Jr., published in the Proceedings of the American Society for Testing and Materials, Volume 49, 1949. Briefly, a cylindrical specimen is bored out in relatively small increments. Longitudinal and tangential strains are measured after each increment. From continuity and equilibrium expressions, it is then possible to determine the longitudinal, tangential and radial stresses removed by each increment of boring. The form of the residual stress equation used in the current work is:

$$S_A = \frac{E}{1 - \nu^2} \left[(A_o - A_b) \frac{d\lambda}{dA} - \lambda \right]$$

$$S_T = \frac{E}{1 - \nu^2} \left[(A_o - A_b) \frac{d\theta}{dA} - \frac{A_o + A_b}{2A_b} \theta \right]$$

$$S_R = \frac{E}{1 - \nu^2} \left[\frac{A_o - A_b}{2A_b} \theta \right]$$

where:

S_A = Longitudinal stress
S_T = Tangential stress
S_R = Radial stress
E = Young's modulus
ν = Poissons' ratio
A_o = Area enclosed by outer surface
A_b = Area enclosed by bored surface
$\lambda = \varepsilon_L + \varepsilon_T$
$\theta = \varepsilon_T + \nu\varepsilon_L$
ε_L = Longitudinal strain
ε_T = Tangential strain

The above expressions assume circular symmetry of stress. Since such was not necessarily to be expected, particularly in the as-received specimens, measurements of strain were made at six equally spaced circumferential locations. The averages of these strains were used as input to the equations above. The individual strain readings were also analyzed for evidence of bending stresses.

2. Instrumentation: Each specimen was instrumented with six Micromeasurements Type MA-06-125-TA-120 two-arm strain gage rosettes. Gages were located at the mid-length of each specimen and were attached with Armstrong Type A-1 epoxy cement. The gages from each specimen were wired into a Lessells and Associates, Inc. precision switch box in such a manner that no connection needed to be broken during the entire test on the specimen and that each gage was read out individually. Two separate dummy gages were used with each specimen in order to provide a cross check.

Strain measurements were taken on a Baldwin Type L strain indicator, strain values being recorded manually.

A thermocouple was placed at the mid-length of each specimen in order to insure against overheating during machining and to provide an indication that temperature had stabilized prior to recording of data.

3. Data reduction: Strain data were transferred to punched cards. The stresses were then computed by an IBM 7094 computer, using the Lessells and Associates, Inc. Residual Stress Program (REST), which is based on the equations noted previously. Results were automatically plotted (by a Stromberg-Carlson 4020 computer recorder) in the form of the graphs included in a succeeding section of this report. The maximum unsymmetrical surface stresses were also computed by the IBM 7094.

4. Boring Procedure: The boring operations were performed in a specially-fixtured lathe, wherein the specimen remained stationary and the tool rotated. This obviated the need for repeated separation of strain gage connections, with the consequent possibility of resistance changes. Specimens were clamped to the crosshead by means of cast iron pillow blocks bored to a close fit with the specimen diameter. These clamps were at the specimen ends, far removed from the gaged area and were arranged so that clamping pressure was only sufficient to prevent rotation of the specimen without producing appreciable distortion. A second set of pillow blocks was placed outboard of the specimen clamps. These blocks were bored and bushed to provide support for the boring bar. The boring bar extended well beyond the boring tool. Thus, the bar was supported by the bushings near either

end of the specimen. This arrangement minimized boring bar deflection and permitted the boring of smaller holes than would be possible with the usual cantilevered arrangement.

The above system evolved during the early portions of the program. The first specimens, B11-3/4 and B2-3/4, were bored somewhat eccentrically. Specimen B11-3/4 was discarded. Symmetry was excellent after the system was developed.

The initial hole in each specimen was drilled. In a few cases the holes were completed by electrospark machining. The first steps of enlargement of holes were accomplished either by drilling or by milling with a relieved end mill. After the third step of hole enlargement, all further machining was performed by boring.

5. Boring Specimens and Test Schedule: In order to ensure against any end effects, the residual stress specimens were made with a length to diameter ratio of five. Thus, the 3/4-inch diameter specimens were 3-3/4 inches in length and the 2-inch diameter specimens were 10 inches in length. The specimens were simple solid cylinders cut from the bar stock with no special preparation other than heat treatment and instrumentation with strain gages and thermocouples.

The schedule of boring tests is given in Table I.

TABLE I. SCHEDULE OF RESIDUAL STRESS DETERMINATIONS - BAR STOCK

Test Condition	Specimen Numbers	
	3/4 Inch	2 Inch
As received	B2-3/4	B1-2
	B3-3/4	B2-2
	B4-3/4	B3-2
	B13-3/4	B4-2
Re-solution, air cool	B5-3/4	B5-2
	B6-3/4	B6-2
Re-solution, oil quench	B7-3/4	B7-2
	B8-3/4	B8-2
Re-solution, air cool, 925°F harden	B9-3/4	B9-2
	B10-3/4	B10-2
As received - 1075°F harden	B1-3/4	B11-2
	B12-3/4	B12-2

C. Stability Tests

In order to determine the long-term dimensional stability of 17-4 PH in different heat-treatment, a number of bars were cut from the as-received stock and subjected to various thermal treatments. Dimensional measurements were taken (a) in the as-received condition, and (b) immediately after thermal treatment and periodically thereafter. Length, diameter and total runout were measured.

Length of the 2-inch specimens was measured with a micrometer with vernier scale to one ten-thousandth inch. Length was measured along the axis of each bar and at three equally-spaced locations around the circumference. Length of the 3/4-inch specimens was measured with a Pratt and Whitney Electrolimit comparator gage, using gage blocks for zero reference. The comparator gage has an ultimate resolution of about one-millionth inch. Considering specimen surface roughness, repeatability in locating the measurement points and temperature variation, the overall accuracy in the measurements is believed to be about ±0.00005 inch per inch of specimen length or about ±.0002 for the 3 3/4 inch length.

Specimen diameter was measured at three equally spaced diameters at specimen mid-length. The comparator gage was also used for this measurement, with an estimated accuracy of ±.0001 inch for the 3/4-inch specimen and ±.0002 inch for the 2-inch specimens.

Specimen runout was also measured with the comparator. The specimen ends were supported in V-blocks mounted to the comparator base. It is believed that these measurements are accurate to about ±0.00005 inch.

Stability specimens are identified in Table II.

TABLE II

TEST SCHEDULE - STABILITY SPECIMENS

Test Condition	Specimen Numbers 3/4 Inch	Specimen Numbers 2 Inch
As received	S1-3/4	S1-2
Re-solution, air cool	S2-3/4	S2-2
Re-solution, oil quench	S3-3/4	S3-2
Re-solution, air cool, 925°F harden	S4-3/4	S4-2
As received - 1075°F harden	S5-3/4	S5-2

D. Simulated Axial Section Tests

A number of specimens were machined to simulate the axial-sensing section of a typical strain gage balance. The design is shown in Figure 1. The specimen is arranged so that the section can be freed by two milling operations which intercept the diagonal slot. The central beams (one on either side) are built in at both ends, a condition not generally typical of balance design. This was done for the purpose of determining any effect of these beams on separation at the midlength of the diagonal slot. These beams are cut at the time the axial section is freed, thus leaving only the eight supporting flexures to hold the two ends of the specimen together. In most actual balances, the axial sensing beams would offer little support in the direction of diagonal slot opening (or closing). Thus, any tendency for distortion in this direction would be free to take place.

At the appropriate stage in the sequence of operation, each specimen was instrumented with eight strain gages, as shown in Figure 2. Strain measurements from individual gages were taken at each step of freeing the section, that is, after making the transverse cuts to free the diagonal slot and after freeing the sensing beams.

Dimensional measurements were taken at each phase of treatment of each specimen. Contour of each of the four faces was determined with respect to a plane through the end points of the particular face. Diameter measurements in the vertical plane were taken at several longitudinal stations. The various points of measurement are indicated with the data in Appendix C of this report.

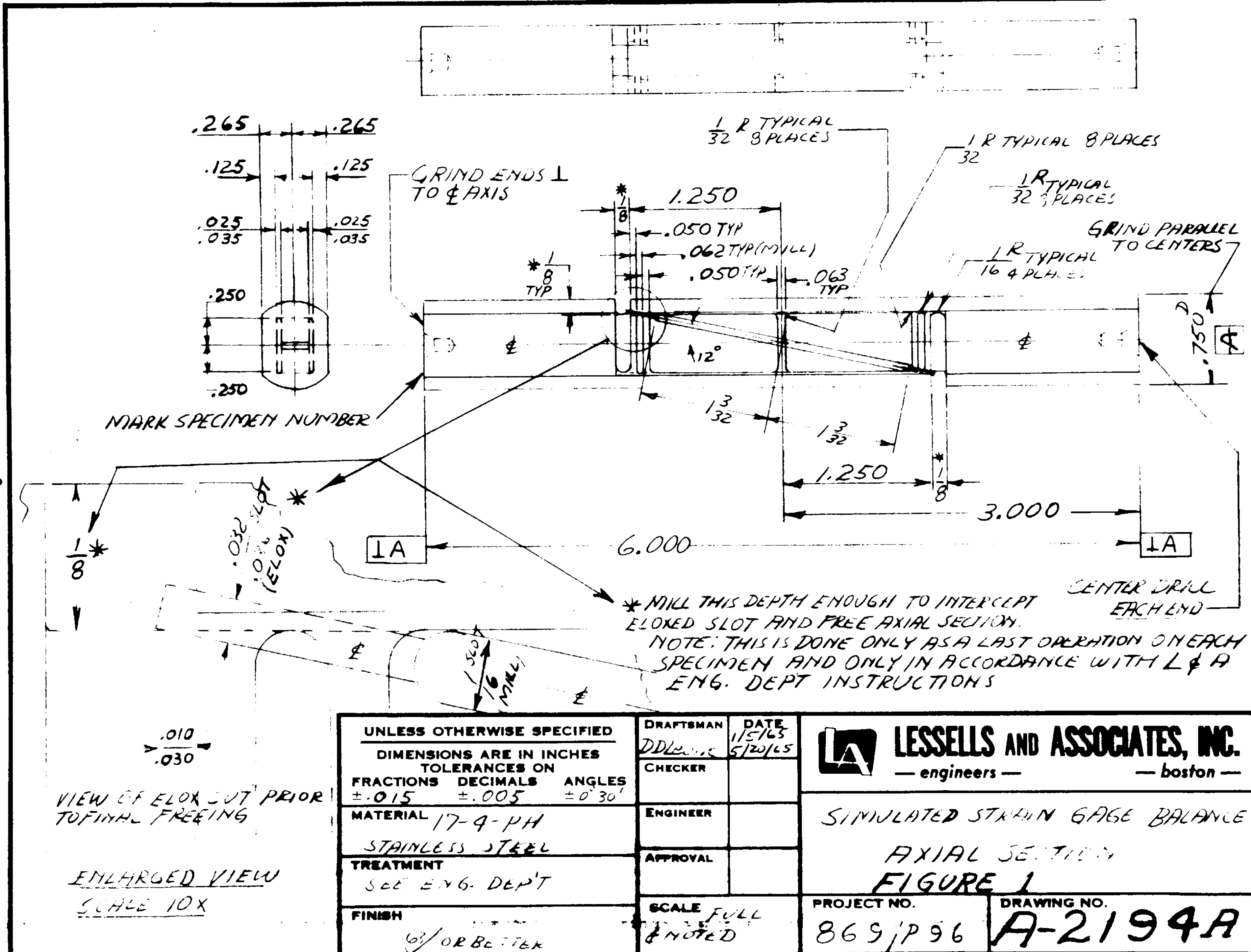
In addition to the above data, temperature measurements were taken during some of the heat treating operations.

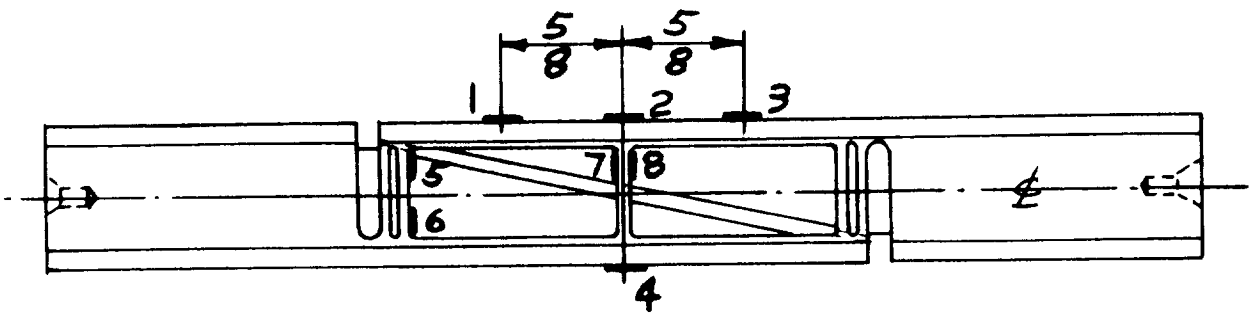
Identification and treatments of the axial specimens are given Table III.

TABLE III

TEST SCHEDULE - SIMULATED AXIAL SECTIONS

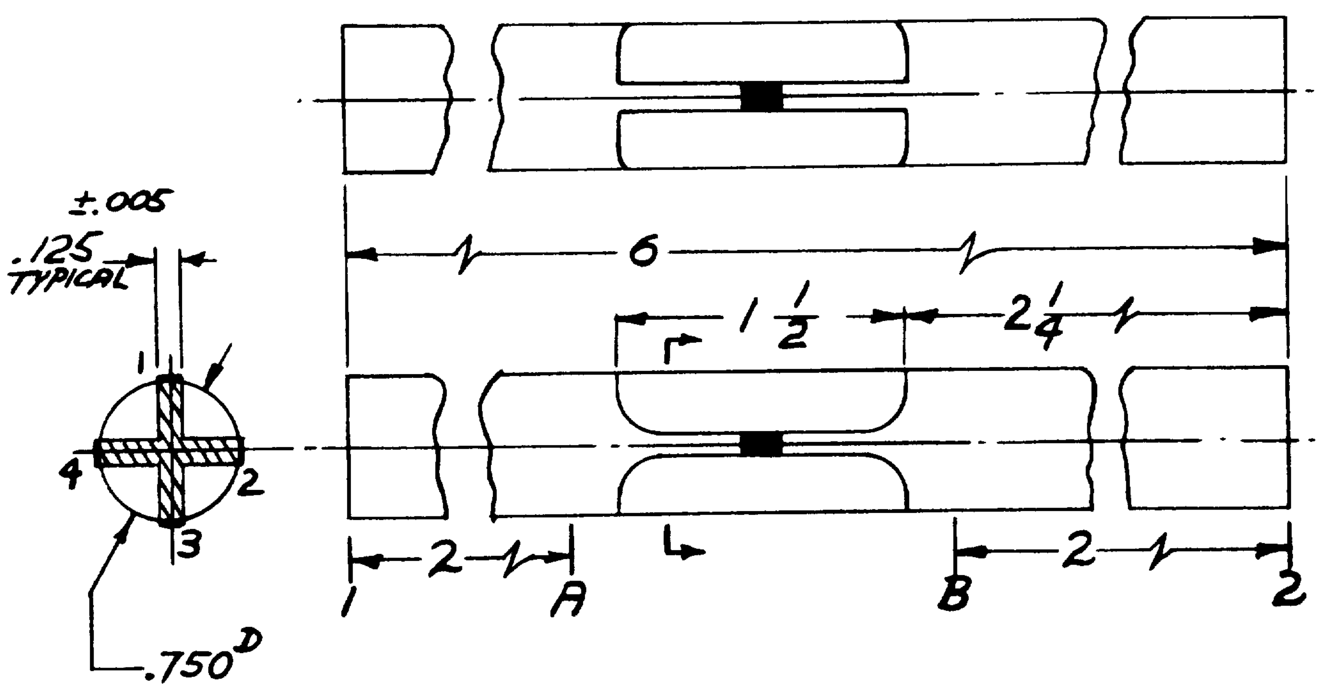
Sequence of Treatment	Specimen Number
Re-solution, air cool, machine, 925^{o}F harden, free	A1, A2
Re-solution, air cool, machine, anneal, 925^{o}F harden, free	A3, A4
Re-solution, air cool, machine, free, 925^{o}F harden	A5, A6
Re-solution, air cool, machine, free, anneal, 925^{o}F harden	A7, A8
As received, 1075^{o}F harden, machine, free	A9, A10


.265
.265
.125
.125
.025 / .035
.025 / .035
.250
.250
MARK SPECIMEN NUMBER
GRIND ENDS ⊥ TO ℄ AXIS
1/32 R TYPICAL 8 PLACES
1/32 R TYPICAL 8 PLACES
1/32 R TYPICAL 8 PLACES
1/16 R TYPICAL 4 PLACES
GRIND PARALLEL TO CENTERS
*1/8 TYP
*1/8
1.250
.050 TYP
.062 TYP (MILL)
.050 TYP
.063 TYP
12°
1 3/32
1 3/32
1.250
*1/8
3.000
6.000
.750 D
A
⊥A
⊥A
CENTER DRILL EACH END
.032 SLOT .036 (ELOX)
1/8*
*
1/16 (MILL)
.010 / .030
* MILL THIS DEPTH ENOUGH TO INTERCEPT ELOXED SLOT AND FREE AXIAL SECTION.
NOTE: THIS IS DONE ONLY AS A LAST OPERATION ON EACH SPECIMEN AND ONLY IN ACCORDANCE WITH L & A ENG. DEPT INSTRUCTIONS
VIEW OF ELOX CUT PRIOR TO FINAL FREEING
ENLARGED VIEW
SCALE 10X
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES ON
FRACTIONS ±.015
DECIMALS ±.005
ANGLES ±0°30'
MATERIAL 17-4-PH STAINLESS STEEL
TREATMENT SEE ENG. DEP'T
FINISH 63/ OR BETTER
DRAFTSMAN
DATE 1/5/63 5/20/65
CHECKER
ENGINEER
APPROVAL
SCALE FULL & NOTED
LESSELLS AND ASSOCIATES, INC.
— engineers —
— boston —
SIMULATED STRAIN GAGE BALANCE
AXIAL SECTION
FIGURE 1
PROJECT NO. 869/P96
DRAWING NO. A-2194A



Gage No.	Type
1, 2, 3, 4	BLH A-8
5, 6, 7, 8	BLH FAP - 06

Figure 2. Strain Gage Locations Axial Specimens



Strain Gages Type BLH FA-12-12

Figure 3. Machining Test Specimen

E. Machining Tests

These tests consisted of the milling of a typical balance cruciform section in specimens of various heat treatments. The configuration of the specimens is shown in Figure 3. Strain gages were attached as indicated in the figure. Dimensional measurements were also taken after each of the various machining steps. In order to determine any adverse effects of machining rate, each quadrant of each cruciform was milled in a single pass, using what would normally be considered a high rate of material removal. The specimen was mounted to the table of a Bridgeport universal milling machine. With a 7/16-inch diameter four-flute end mill, operating at 325 RPM, the specimen was fed into the cutter manually to full depth of cut. The cut was then made for the full length of the cruciform, (at full depth), at a rate of one inch per minute, using a climb cut. Measurements of specimen temperature were made during each cut.

On the first specimen tested, diagonally opposite quadrants were cut first. It was presumed that this would be less likely to create distortion than would the case of adjacent quadrants first. As will be seen in the results, essentially no final distortion occurred, so later cutting was restricted to the case of adjacent quadrants first. It was also planned to perform some machining at reduced cutting rates and depths. Since little final distortion occurred at the more severe conditions, this reduction was not made in later specimens. It will be noted that two specimens in the 1075°F condition were tested identically. This was done for confirmation of results for this case in which some particular intent has been expressed.

Table IV lists the specimens and test conditions for the machining tests.

TABLE IV

TEST SCHEDULE - MACHINING SPECIMENS

Test Condition	Specimen Number
Re-solution, mill diagonal quadrants first	M1
Re-solution, mill adjacent quadrants first	M2
Re-solution, 925°F harden, mill adjacent quadrants first	M3
As received, 1075°F harden, mill adjacent quadrants first	M4
As received, 1075°F harden, mill adjacent quadrants first	M5

V. RESULTS AND DISCUSSION

A. Residual Stress Determinations

The computer plots of the symmetrical residual stress tests on 3/4-inch and 2-inch bar stock are shown in Appendix A. Please note that Specimens B1-3/4 and B13-3/4 are out of sequence relative to thermal treatment but are included in numerical sequence in Appendix A. Also, please note that there is no Specimen B11-3/4.

Longitudinal, tangential and radial stresses are plotted versus radius for each specimen and identified on the plots by the symbols A, T and R, respectively. For ease in comparison, all plots of each bar size are plotted to the same scale.

When examining the plots, it should be kept in mind that the sensitivity of the boring method is such that very small errors in strain readings can result in very large errors in calculated stress at the smaller radii. For example, on a two-inch specimen, an error of five microinches per inch corresponds to a stress of about 35,000 psi. This situation improves rapidly with increasing bore radius. Thus, rapid fluctuations or unusual values in stress at the smaller radii should not be weighed heavily.

The longitudinal stresses are of principal interest in strain gage balance applications, since they are responsible for the distortions in the typical design; for example, general curvature over the length of the balance or curvature at sections where much material is removed by machining.

1. 3/4-Inch Specimens

For comparative purposes, a composite plot of these longitudinal stresses is shown in Figure 4. Each curve is the average, as estimated by eye, of the specimens for that condition.

Looking first at the as-received condition, it is seen that very high tensile stresses are present near the center, being approximately 85,000 psi at the first point of measurement. The stress level drops to zero at a radius of about 0.22 inch and continues into compression to a maximum of about -20,000 psi at the last point of measurement. This is the condition which would be expected from the heavy surface cold working during straightening. The action of the rollers at the surface plastically deforms the surface material, forcing it to elongate in the longitudinal direction through action of compressive stress. This outer material, through shearing action, attempts to pull the center material along with it, creating longitudinal tensile stress in the center portion. This action is quite evident from the severe cupping of the bar ends in the as-received condition. The machining of a bar in this condition would result in considerable distortion. For example, if the bar were split longitudinally, the material near the center would shorten and the material near the surface would elongate, with a resultant bending of the two sides in the direction tending to close the split. If instead, material were

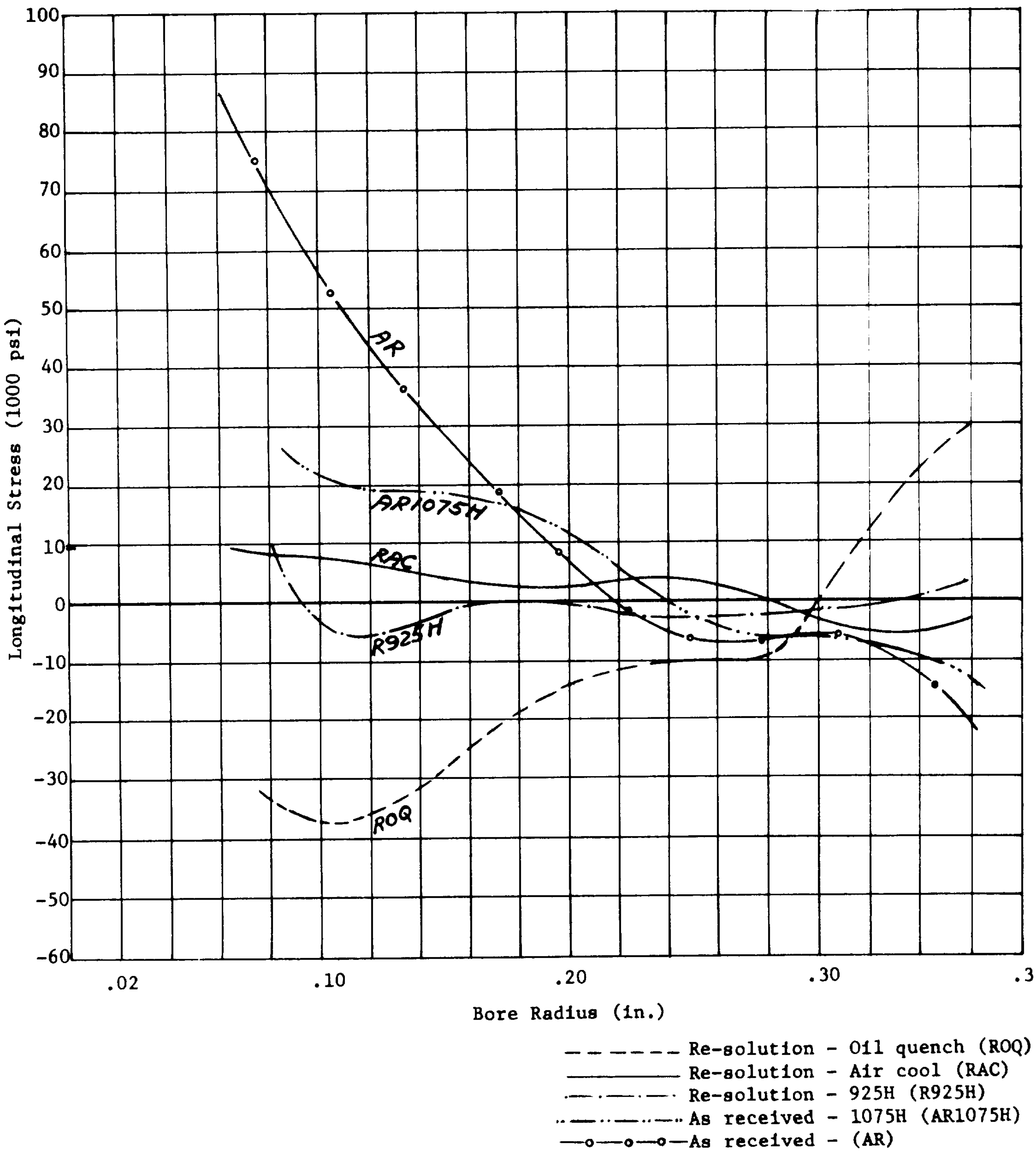


Figure 4. Longitudinal Stresses in 3/4-Inch Specimens - Composite Plot

to be turned off of the outer diameter, the stresses indicated here would result in a shortening of the remaining portion up to nearly 0.003 inch per inch of length, depending on the amount of material removed. Special machining operations, such as those involved in the construction of strain gage balances, could result in many combinations of the distortions. Thus, the as-received condition is highly undesirable for use in the manufacture of precision devices.

Referring again to Figure 4, the operation of re-solution treating and air cooling can be seen to have removed practically all of the residual stress, leaving a maximum value of the order of 10,000 psi near the center (the region of least experimental accuracy) and a maximum of about 5,000 psi throughout the remainder of the material. Similarly low stresses result from the 925°F hardening treatment when it is preceded by re-solution treatment. Thus, either of these procedures would give nearly stress-free material, an ideal situation from the point of view of distortion during machining.

Oil quenching from re-solution temperature, also indicated in Figure 4, gives large residual stresses of opposite sign to those in the as-received condition. These must arise from volume changes during transformation, where this transformation takes place at the outer surface before it occurs at the hotter center of the bar. Stresses arising purely from thermal gradient would be of opposite sign. Thus, the oil quenching procedure is quite evidently undesirable if stress-free material is to be obtained.

The last treatment shown in Figure 4 is that wherein the as-received material was precipitation-hardened at 1075°F. Although the stresses are reduced from the original condition, they remain about two to three times as high as those from re-solution treatment with air cool and with or without the 925°F hardening treatment. Thus, this treatment ranks in desirability in between the others. It should be mentioned that the case of 1075°F hardening following re-solution treatment was not tested. It appears quite likely that this would be a satisfactory procedure, allowing hardening prior to machining and still leaving an easily-machinable condition.

The maximum computed surface bending stresses for the 3/4-inch specimens are given in Table V.

TABLE V

SURFACE BENDING STRESS - 3/4-INCH SPECIMENS

Treatment	Specimen	Bending Stress (psi)	Average (psi)
As received	B2-3/4	16,500	12,500
	B3-3/4	8,100	
	B4-3/4	21,000	
	B13-3/4	4,500	
Re-solution, air cool	B5-3/4	5,000	3,300
	B6-3/4	1,600	
Re-solution, oil quench	B7-3/4	8,500	4,400
	B8-3/4	300	
Re-solution, 925°F harden	B9-3/4	5,000	6,500
	B10-3/4	8,000	
As received, 1075°F harden	B1-3/4	5,500	7,250
	B12-3/4	9,000	

It can be seen that the as-received condition exhibits the highest average level and also large variations from specimen to specimen. This is consistent with the random straightening operation. The as received, 1075°F hardened group shows the next highest average stress, perhaps reflecting the presence of some of the original straightening stresses. The re-solutioned, 925°F hardened group also shows some bending stresses, although the values in both of these last two groups are low enough to be of little concern. The re-solutioned with air quench and oil quench groups have had the bending stresses almost completely removed.

Thus, only the as-received condition appears to be undesirable from the point of view of residual bending stress. Any of the heat treatments relieves appreciable amounts of this stress, the 1075°F hardening being least effective. A re-solution treatment followed by 1075°F hardening might be more effective. This condition was not tested.

2. Two-Inch Specimens

Composite results for the two-inch specimens are plotted in Figure 5. As in the 3/4-inch specimens, the highest stresses are

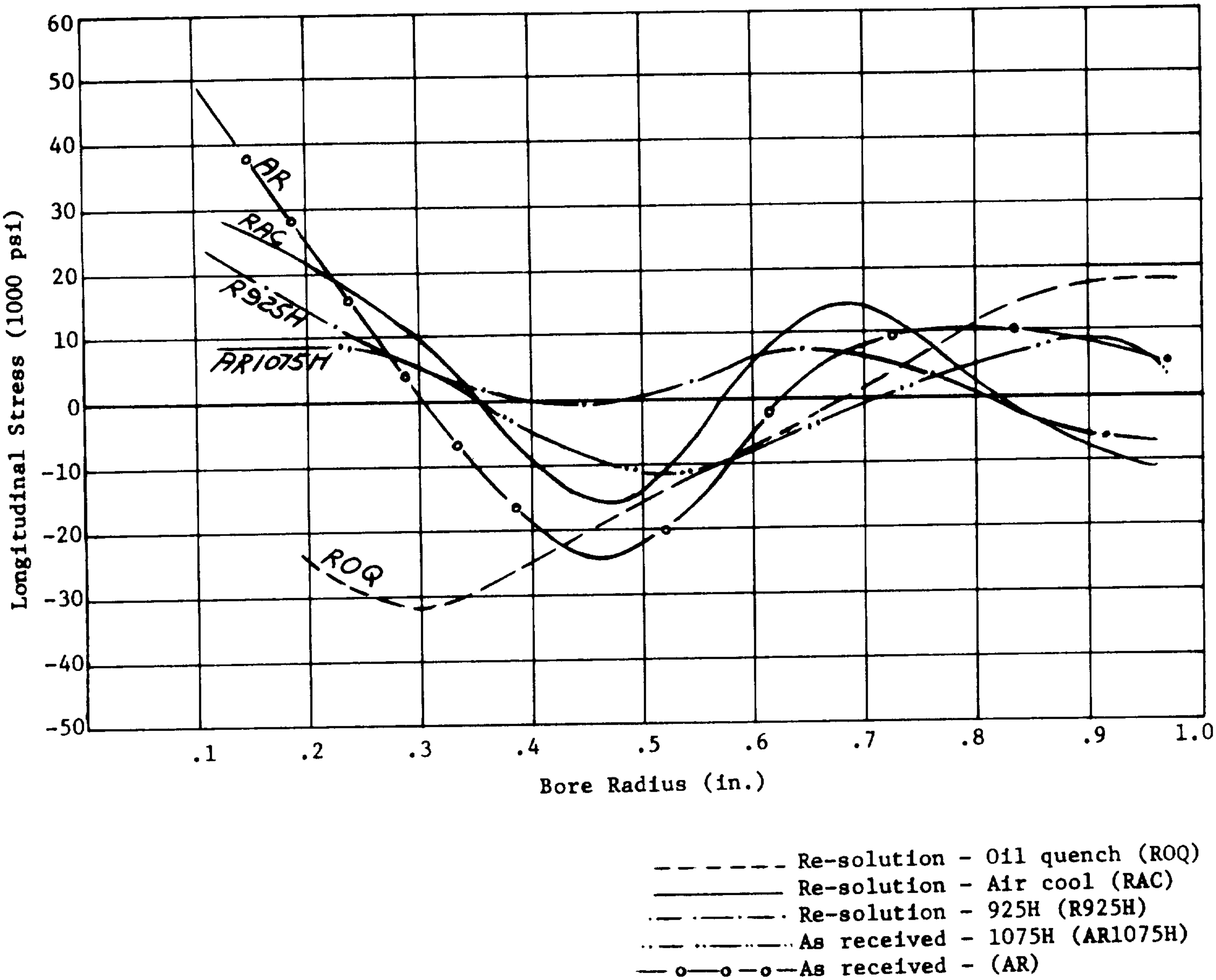


Figure 5. Longitudinal Stresses in Two-Inch Specimens - Composite Plot

present in the as-received condition. The magnitudes are somewhat lower, with an average maximum measured value of about 50,000 psi. The distribution is also somewhat different in that a portion near mid-radius is in compression, with tension near the outer surface.

It might be expected that the extreme surface stress would be compressive, although the boring tests did not continue that far. This argument is supported by the requirement for force equilibrium which would appear to demand some additional compressive force. (Tensile and compressive areas of longitudinal stress must balance when plotted versus bored area.)

The re-solution treatment followed by oil quenching had the same effect as in the 3/4-inch specimens, creating compressive stress near the center and tensile stress near the outside. This again, could be considered an undesirable condition for use in precision machining.

The re-solution treatment, with air cooling, did not result in the nearly stress-free condition of the 3/4-inch specimens. In addition to a peak of about 30,000 psi near the center, there are negative and positive peak stresses of about 15,000 psi at mid-radius. No explanation of this is apparent. It is noted, however, that the curve bears considerable similarity in shape to that of the as-received condition, but with lower magnitudes of stress. This indicates the possibility of insufficient time at temperature to relieve the original residual stress.

Both the re-solutioned, 925°F hardened and the as-received, 1075°F hardened materials indicate reasonably low stresses, although the 925°F hardened material shows a peak of about 30,000 psi near the center (again, the region of poorest measurement accuracy). Other than at that region, the 925°F hardened condition shows slightly lower stresses than the 1075°F condition. Thus, based on these particular tests, either of these two treatments could be considered satisfactory. It should be remembered, however, that the as-received, 1075°F hardened material in 3/4-inch size did not show up particularly well. Thus, some caution should be advised in using this treatment. A small amount of additional investigation of these treatments might be indicated.

The maximum surface bending stresses for the two-inch specimens are given in Table VI.

TABLE VI

SURFACE BENDING STRESSES - 2-INCH SPECIMENS

Treatment	Specimen	Bending Stress (psi)	Average (psi)
As received	B1-2	37,000	
	B2-2	——	19,600
	B3-2	14,000	
	B4-2	7,800	
Re-solution, air cool	B5-2	9,000	5,500
	B6-2	2,000	
Re-solution, oil quench	B7-2	16,500	27,250
	B8-2	38,000	
Re-solution, 925°F harden	B9-2	22,500	16,500
	B10-2	10,600	
As received, 1075°F harden	B11-2	6,500	14,250
	B12-2	22,000	

The bending stresses are considerably higher than those observed in the 3/4-inch specimens. Any of the thermal treatments, other than oil quenching, reduces the stresses appreciably. It can be seen that the re-solution treatment with air cool gives the lowest stress, but subsequent 925°F hardening appears to increase the bending stress again. Reasons for this are not apparent. It should be kept in mind that drift in a single gage reflects directly in these values, whereas it is averaged out in the computation of the symmetrical stresses. Thus, the reliability of the bending data is not as good.

Based on the average results in Table VI, the as-received, 1075° hardened or the re-solutioned, 925°F hardened treatment are about equal. Thus, there is not much choice between the two. As mentioned previously, a re-solution treatment prior to 1075°F hardening might offer some improvement.

B. Stability Tests

Detailed data from the stability tests are presented in Appendix B. Data include the changes in dimension before and after heat treatment as well as repeated measurements over a period of months after treatment. Because of slight scale buildup and/or flaking, the changes during solution-treating are not quite as accurate. Nevertheless, the following trends are clear:

Re-solution treating followed by air cooling, air cooling and 925° hardening, or by oil quenching produced a net decrease in length of about 0.0005 inch per inch in both specimen sizes. It produced 0.0001 to 0.0006 inch of diameter increase (neglecting one questionable point of 0.00252 inch) rather randomly distributed between both sizes (possibly scale buildup).

The as-received, 1075°F hardened specimens showed decreases in diameter, during hardening, of about 0.0005 to 0.0013 inch per inch and decreases in length of about 0.0005 inch per inch.

No really significant trends are apparent in the long-term data. The largest variation noted is a decrease in the value of dimension D3, Specimen S2 - 3/4, of 0.00345 inch. This is offset by an increase in D2 of +0.0025 inch, so is probably experimental error. Thus, there is nothing to indicate that lack of long-term stability is a practical problem with any of the heat treatments.

C. Simulated Axial Section Tests

Detailed data from these tests are given in Appendix C.

1. Height and Length Changes

Looking first at Table C-1, changes in height and length, as determined by micrometer measurements, are given in terms of the total change from the as-machined condition, in units of ten-thousandths of an inch. It should be remembered that all except Specimens A9 and A10 had been re-solution treated prior to machining. The latter two were hardened at 1075°F prior to machining. It can be seen that the large majority of the changes are small, i.e., 0.0005 inch or less. The following significant changes are seen:

a) Treatment at 1900°F after machining but either before or after freeing, produces significant decreases in length beyond those expected from hardening alone. This is evidenced in Specimens A3, A4, A7, and A8.

b) Less conclusive, but evidenced in Specimens A3 and A8, is a bowing at the mid-length in the form of separation or closure across the diagonal slot when the 1900°F treatment followed machining. It is noted that Specimen A8 improved in this regard after opening during the freeing operation. Nevertheless, movement did take place during the 1900°F treatment.

c) Freeing prior to post-machining heat treatment caused diagonal slot separation (as above) in Specimens A6 and A8.

d) Excessive diagonal slot separation resulted from freeing of Specimens A9 and A10, which had been hardened at 1075°F prior to machining.

Rating the various processes, <u>based on the height and length data only</u> and considering small length changes as unavoidable during hardening, Specimens A1 and A2 are best, A5 and A6 next best, and the others about tied for third place, depending on the relative importance of the different types of distortion. Thus, the material should be re-solution treated prior to machining, machined, hardened and freed. Reversing the last two operations may be slightly detrimental.

2. Contour Changes

Table C2, in Appendix C, gives all specimen contour data in terms of change from the as-machined condition. The data represent ten-thousandth-inch changes, with positive values representing outward movement of the face in question. An analysis of the data leads to a listing of the significant changes between the machined condition and the final condition, as shown in Table VII.

TABLE VII

SIGNIFICANT CONTOUR CHANGES - AXIAL SPECIMENS

Specimen Number	Vertical Curvature (in.)	Lateral Curvature (in.)	Slot Opening (in.)
A1	0.0002	0.0002	0
A2	0.0003	0.0001	+0.0003
A3	0.0005	0.0032	-0.0008
A4	0.0008	0.0033	-0.0016
A5	0.0002	0.0004	0
A6	0.0004	0.0005	+0.0009
A7	0.0009	0.0052	-0.0011
A8	0.0007	0.0013	+0.0002
A9	0.0002	0.0003	+0.0033
A10	0.0001	0.0005	+0.0034

The largest distortions are in lateral curvature (Groups A3, A4 and A7, A8) and in slot opening (Groups A9, A10). These distortions are all of sufficient magnitude to arouse concern over the proper functioning of a strain gage balance. The first type would cause interactions between components, whereas the second type would apply a prestrain to the axial sensing elements, at least of certain types. Groups A1, A2 and A5, A6 show quite small distortions, the former being slightly smaller. Thus, the optimum sequence of treatment, based on contour data, appears to be re-solution treatment, machining, 925°F hardening and freeing. Reversal of the last two may be only slightly disadvantageous. It should be mentioned again that the parallel case, but involving 1075°F hardening was not tested. This might well prove to be equal or better than the best of the above.

3. Strain Gage Data

Detailed strain gage data taken during the freeing operation are given in Table C3. It is seen that the highest strains were observed in Specimens A9 and A10. The first cuts at the ends produced primarily a relative axial shortening, as evidenced by strains of opposite signs on the vertical members. Subsequent parting of the central vertical members released large strains in the vertical members and allowed curvature of the upper and lower horizontal members in the direction of slot opening. The highest strain of 1185 microstrain, corresponding to a stress of approximately 30,000 psi, was on the stiff central vertical member. This type of member is not normally used as a sensor, being much more rigid. It was included to supply restraint and a subsequent measure of the deflection across the slot. Thus, it provides an indicator of the degree of deflection to be encountered by a more usual, softer type of axial sensing element.

The next highest strains were found in Specimens A7 and A8, which were freed immediately after machining and prior to final heat treatment. These are of the same form but of considerably lower magnitude than those found in Specimens A9 and A10. Strains in Specimens A5 and A6 were somewhat lower, although these specimens were in the same condition as A7 and A8 at the time of freeing, differences being only in subsequent treatment.

The smallest strains were observed in the first two groups, the second group being the lowest. Thus, from the strain gage data, it appears that the 1900°F treatment subsequent to machining is beneficial in that it produces a relatively strain-free balance. It should be recalled, however, that the treatment caused considerable distortion. This would not be observed by the strain gages, since they were not installed until after final heat treatment.

4. Temperature Gradients During Thermal Treatment

A few of the axial specimens were instrumented with thermocouples during the heat treatment operations in an effort to determine temperature gradients between the thin and thick sections of the specimens.

During the 1900°F re-solution treatment measurements, all but one of the thermocouples failed as the maximum temperature was reached. These failures were due to the sharp bends imposed on the wires as they passed through the sand seal on the retort used to maintain the Argon atmosphere. Evidently as the specimens, retort, and wiring reached a glowing red condition at 1900°F the thermocouples failed one at a time. No reliable data were obtained during this test.

The 925° treatment was performed in air so this wire routing problem didn't exist. Because of the unavilability of automatic recording equipment, there was a switching time lag between temperature readings. Therefore, gradients were not reliably determined.

The data are presented in Table C4 without discussion.

5. Summary of Axial Section Tests

Considering the various tests on these specimens together, a consistent pattern is evident. First, a re-solution treatment prior to machining is beneficial, as evidenced by the poor performance of those specimens which were 1075°F hardened in the as-received condition. Second, solution treatment after machining is detrimental in that it produces high distortion, although it does result in the least residual stress at the time of freeing the balance. In cases where the part can be rough-machined, solution treated, hardened and then finish machined and freed, this treatment might be satisfactory. Third, the procedure of solution-treating, machining, 925°F hardening and freeing stands out as the best all-around procedure, although the residual stresses released on freeing were only the second lowest observed. Reversing the hardening and freeing operations is not quite as good. Finally, the case of solution-treating, 1075°F hardening and machining might be expected to be satisfactory. This case was not tested in the current program.

D. Machining Tests

Detailed data obtained from the machining tests are given in Appendix D. Because of the proximity of the cutting tool to the strain gages and the rather high temperatures developed, no strain gage data were obtained. Runout data, however, indicate clearly the distortions encountered during the machining.

The only significant distortions encountered during any of these tests took place during milling of the first two adjacent quadrants of the 1075°F hardened material, amounting to a net increase in total diametral runout of 0.0024 inch. Upon milling the last two quadrants, all but 0.0006 inch of this runout had disappeared. Thus, even this exceptionally heavy cutting did not significantly influence the response of the material. Lighter cutting rates might have shown some improvement (and are generally desirable for precision work). The observed distortion, moreover, was probably caused by release of residual stresses in the material rather than by high machining rate, since none of the re-solution treated materials exhibited significant distortion. Thus, even under the worst conditions tested, rough machining to within 0.002 to 0.005 inch of finish dimension, followed by a finish cut,should enable the creation of accurate sections.

Temperature in the vicinity of the milling cutter generally ranged from about 300°F to 450°F. The maximum observed was 530°F. This was on the last cut of the program, after the same tool had been used for all previous cuts. The increase in temperature was probably caused by dulling of the tool.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. The 17-4 PH bars as received contain high residual stresses, up to approximately 90,000 psi maximum.

2. Solution treating (with air cool) the as-received material serves to remove nearly all the residual stress in the 3/4-inch bars and the major portion of that in the 2-inch bars.

3. Oil quenching from solution temperature introduces stresses of sign opposite those of the as-received material and of magnitude up to about 50,000 psi.

4. Hardening the as-received material to the 1075 H condition, without prior solution treatment, only partially relieves the residual stress.

5. Solution-treating after machining results in linear (and presumably volume) changes greater than those caused by precipitation-hardening treatments, although low final stresses result.

6. The combination of physical distortion and gage strains is lowest for the cases where the material was solution-treated, hardened at 925°F and freed, or solution-treated, freed and then hardened at 925°F. The latter case is slightly worse with regard to distortion.

7. Long-term dimensional stability of the material in every treatment tested was high.

8. High cutting rates in machining processes do not introduce appreciable stresses in either the solution-treated or the as-received, 1075°F hardened material.

B. Recommendations

1. The optimum procedure (of those tested) for application to manufacture of strain gage balances is: a) re-solution treat the as-received material, b) machine, c) harden at 925°F, and d) free the axial sections.

2. The second choice in procedure is the same as above except that the axial section is freed prior to hardening.

3. In cases where finish machining after elevated temperature treatment is possible, a solution-treatment after rough machining may be beneficial. Considerable distortion may occur during solution treatment.

4. Hardening the as-received material at 1075°F prior to machining is not recommended. If it is desired to use 1075°F hardened material, prior solution treatment would probably make this condition acceptable. Some investigation of this case is recommended.

5. The case of solution treating and 925°F hardening prior to machining was not studied. Should there be a desire to apply this procedure, some investigation is recommended.

6. Some additional study of the re-solution treatment of two-inch bars is recommended. The reduction of residual stress in these bars was not as complete as in the 3/4-inch bars. Longer time at temperature or controlled cooling rate might improve this situation.

APPENDIX A

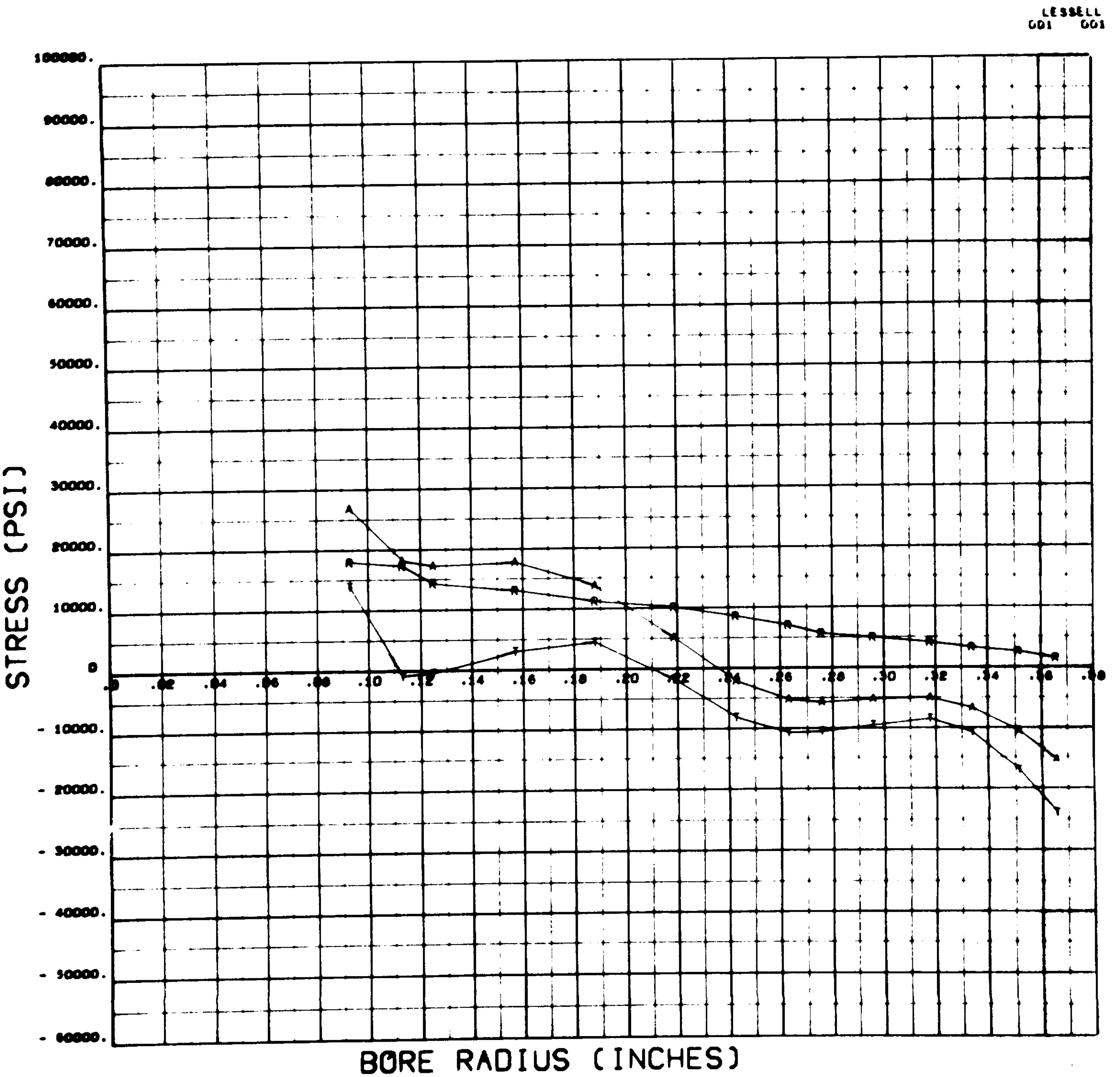
RESIDUAL STRESS DATA

Symbols on curves are:

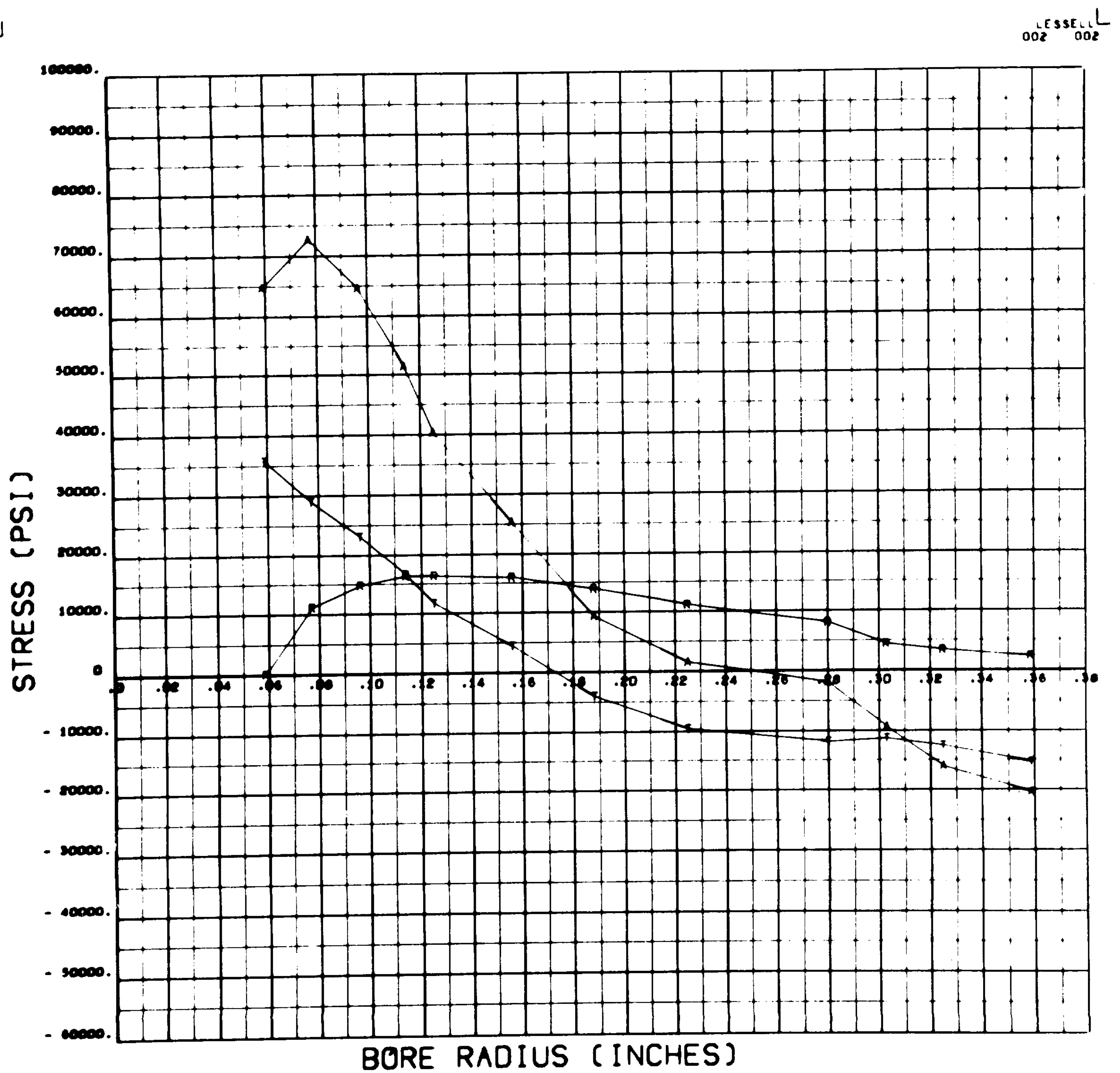
A = Longitudinal stress
T = Tangential stress
R = Radial stress

Figures in this section are in numerical order by specimen number. Please refer to Table I of the text for heat treatment code.

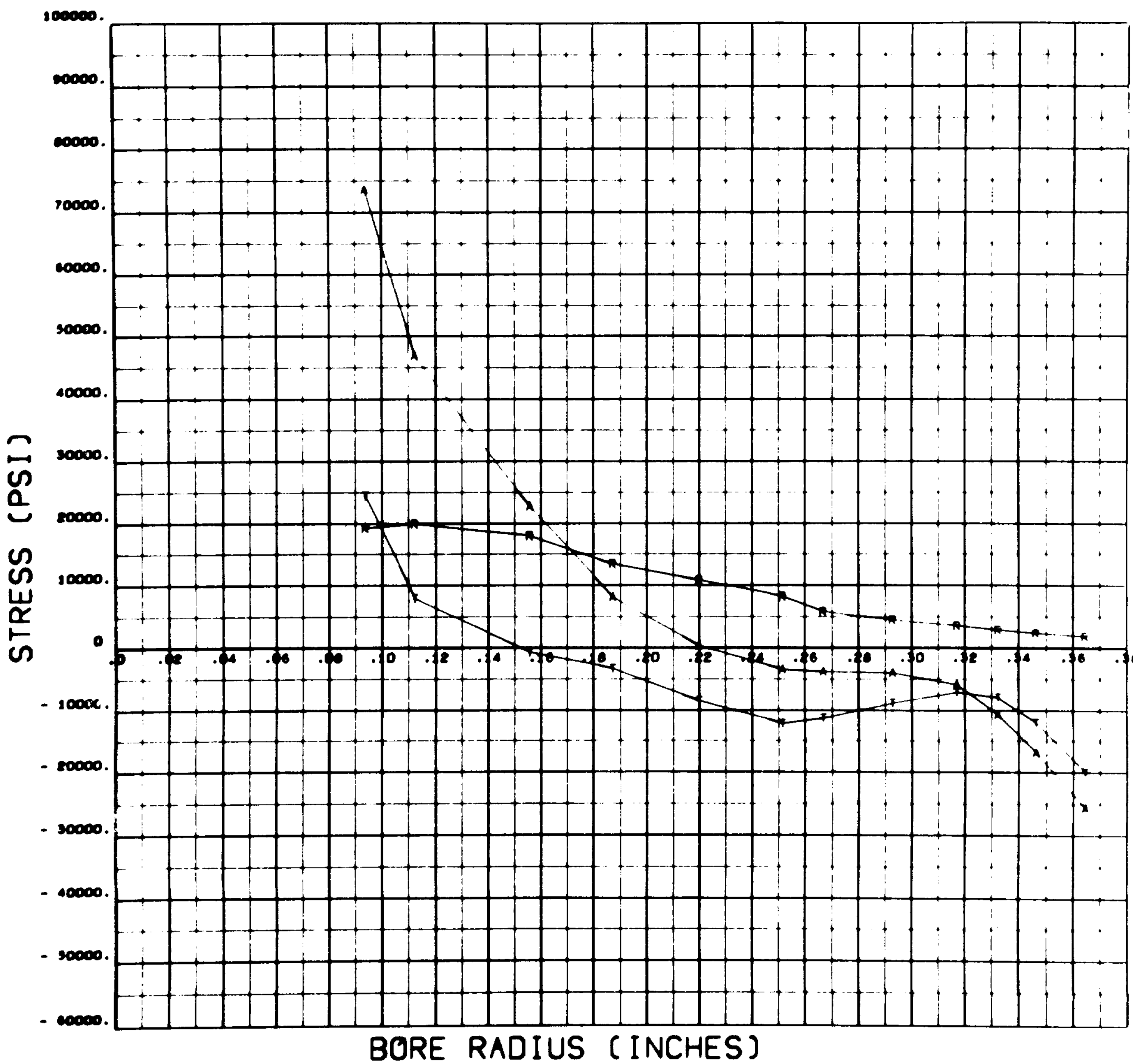
Specimen B1-3/4 through B13-3/4 (except no Specimen B11-3/4)
Specimen B1-2 through B12-2



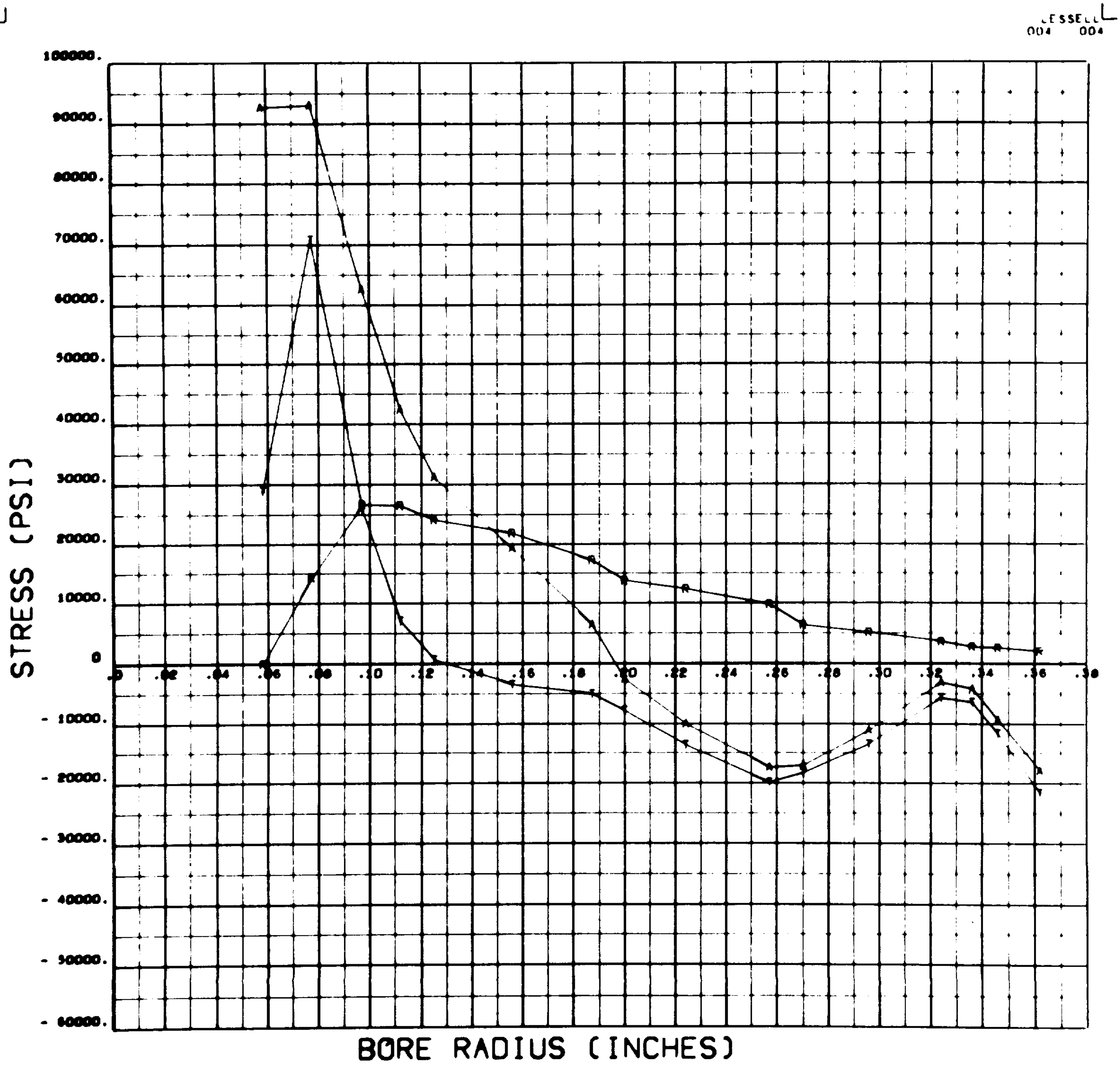
STRESS VS. RADIUS - SPECIMEN B1-3/4



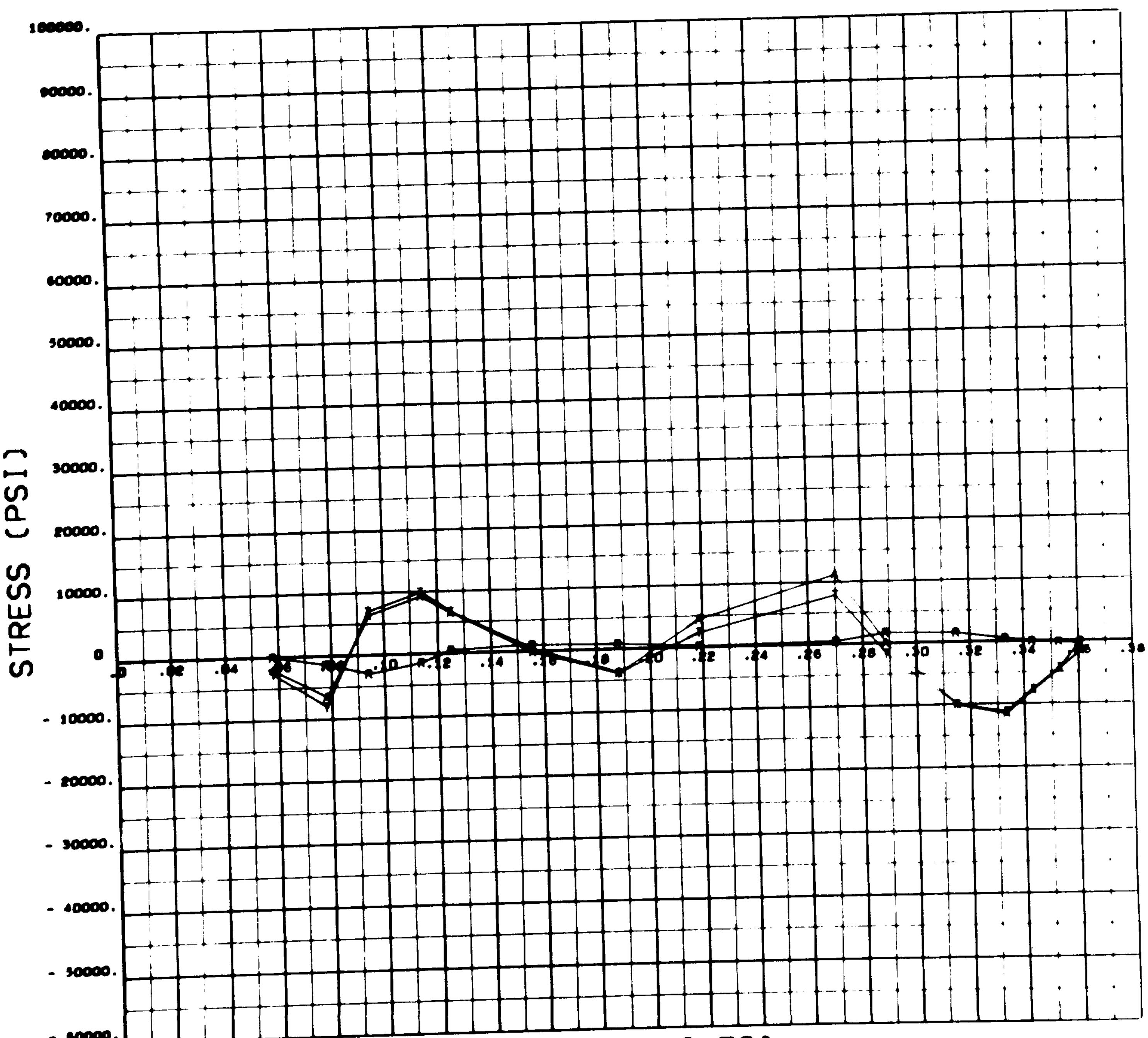
STRESS VS. RADIUS - SPECIMEN B2-3/4



STRESS VS. RADIUS - SPECIMEN B3-3/4

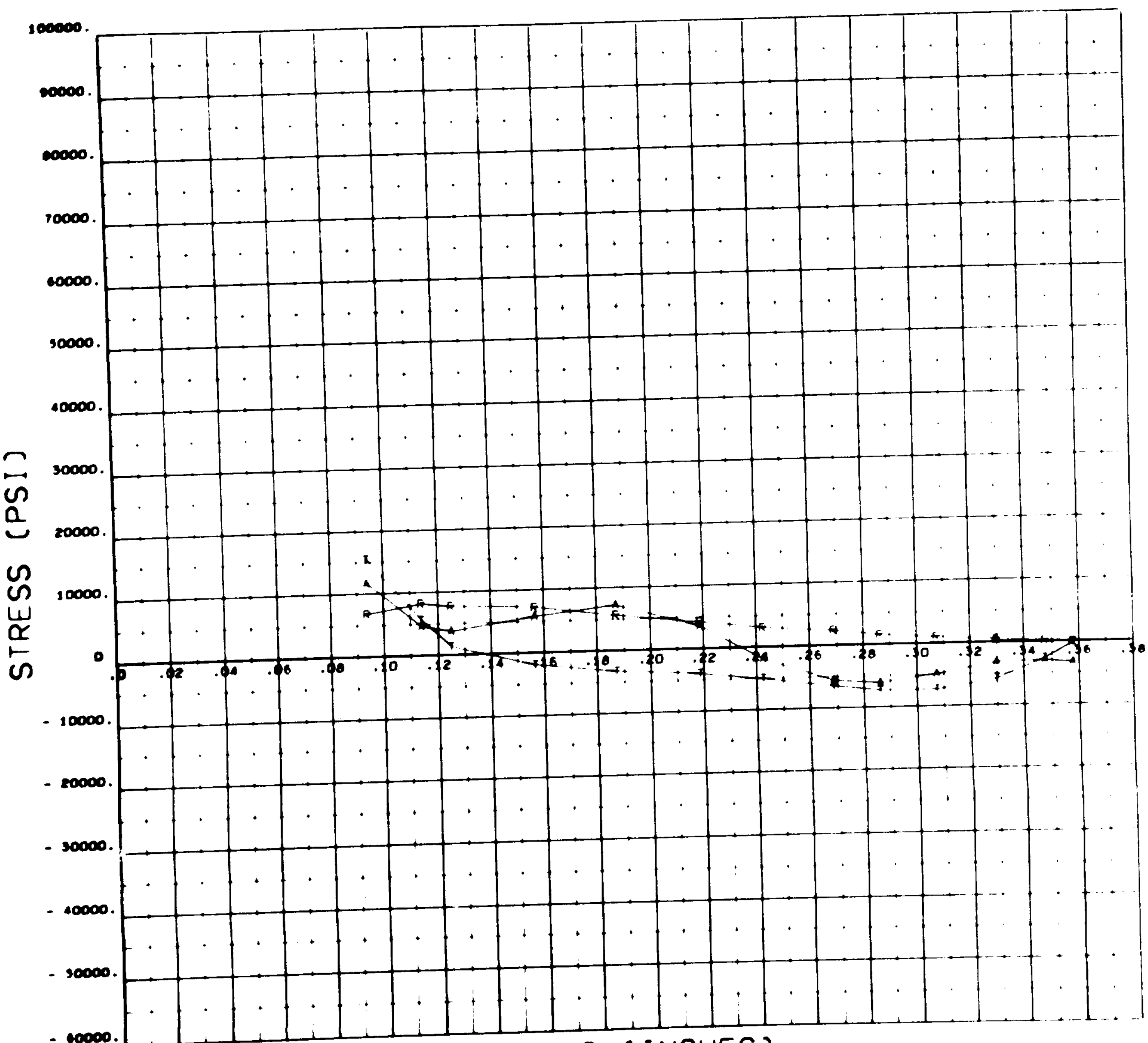


STRESS VS. RADIUS - SPECIMEN B4-3/4

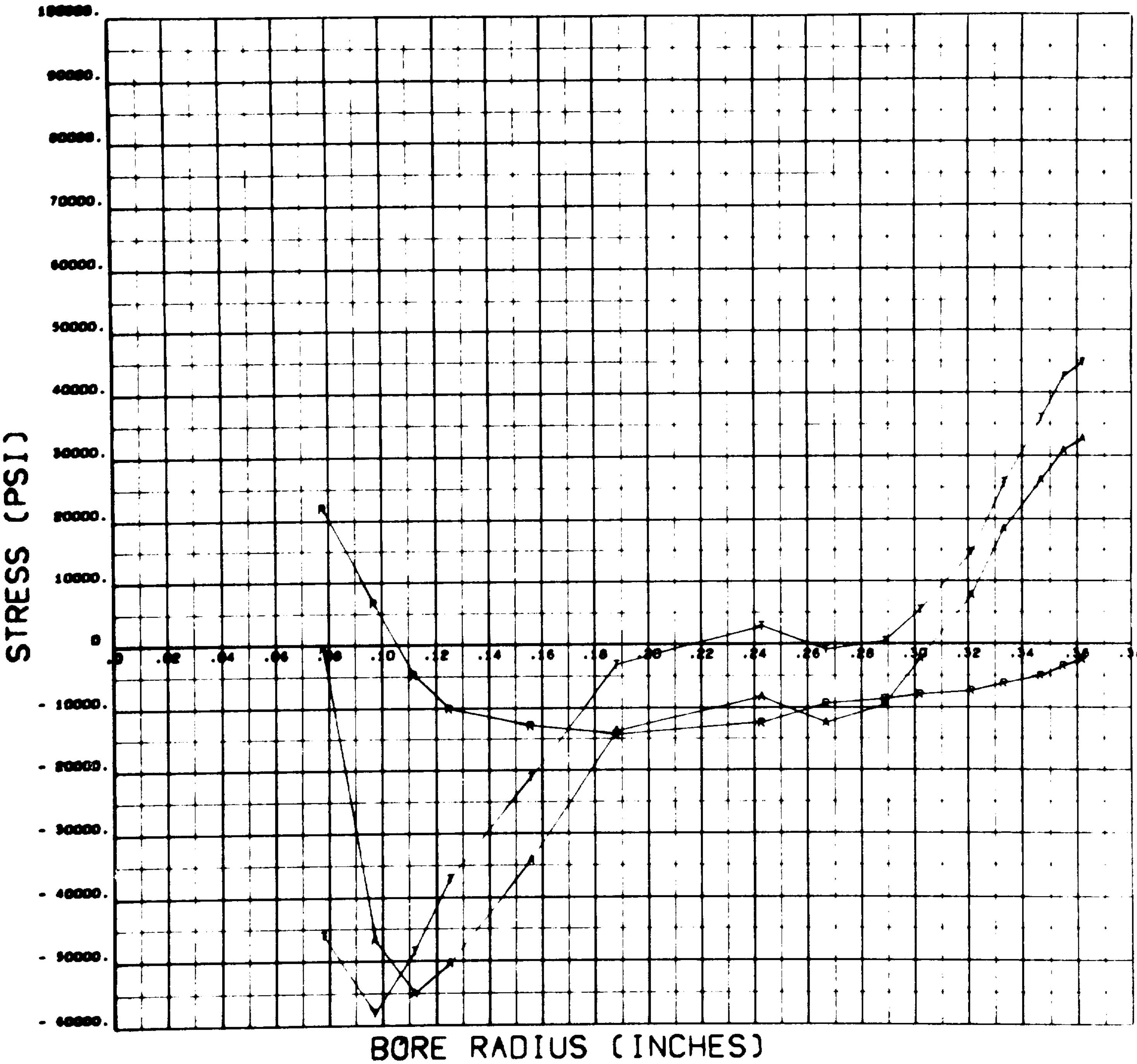


BORE RADIUS (INCHES)

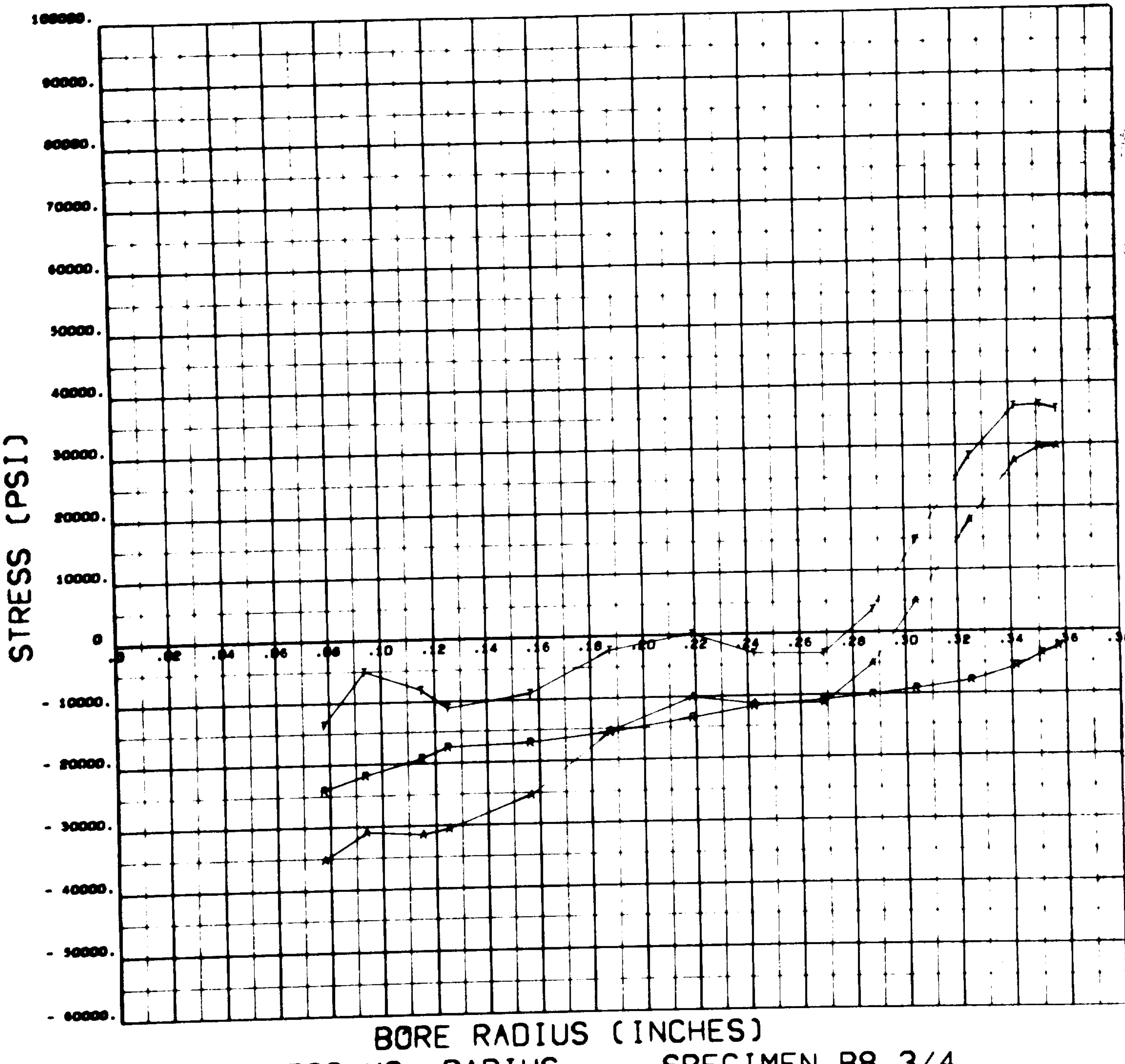
STRESS VS. RADIUS - SPECIMEN B5-3/4



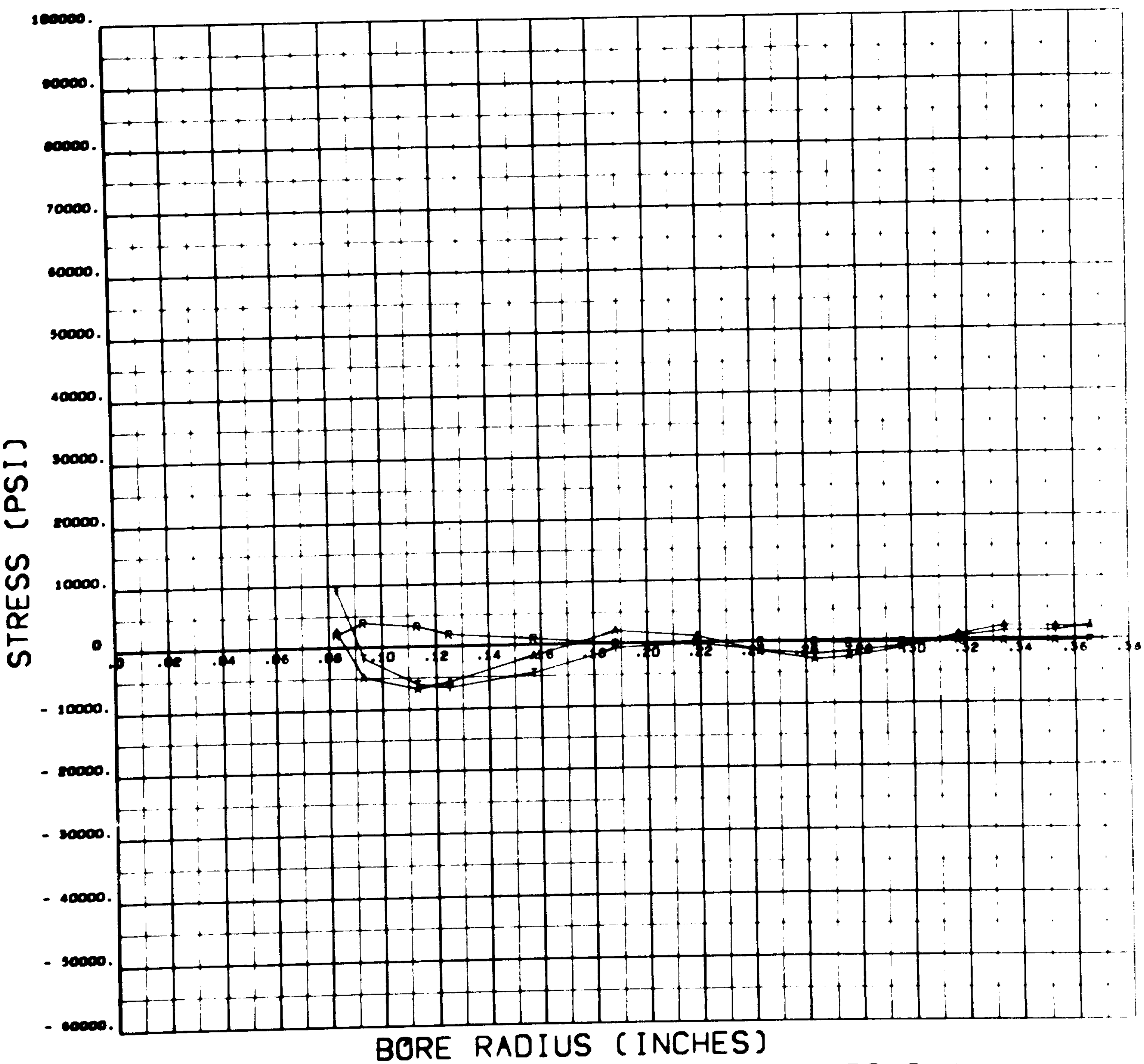
STRESS VS. RADIUS - SPECIMEN B6-3/4



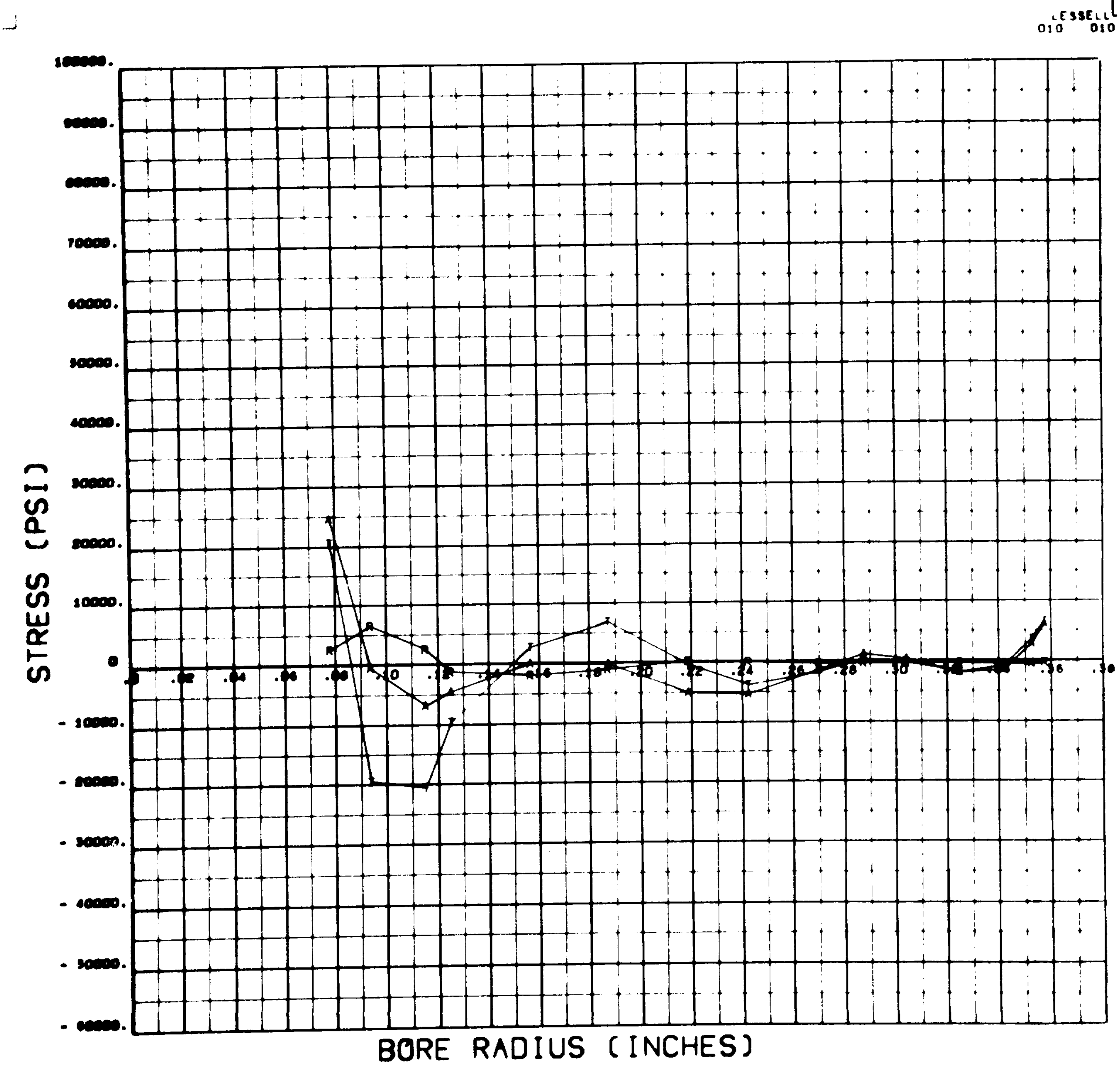
STRESS VS. RADIUS - SPECIMEN B7-3/4



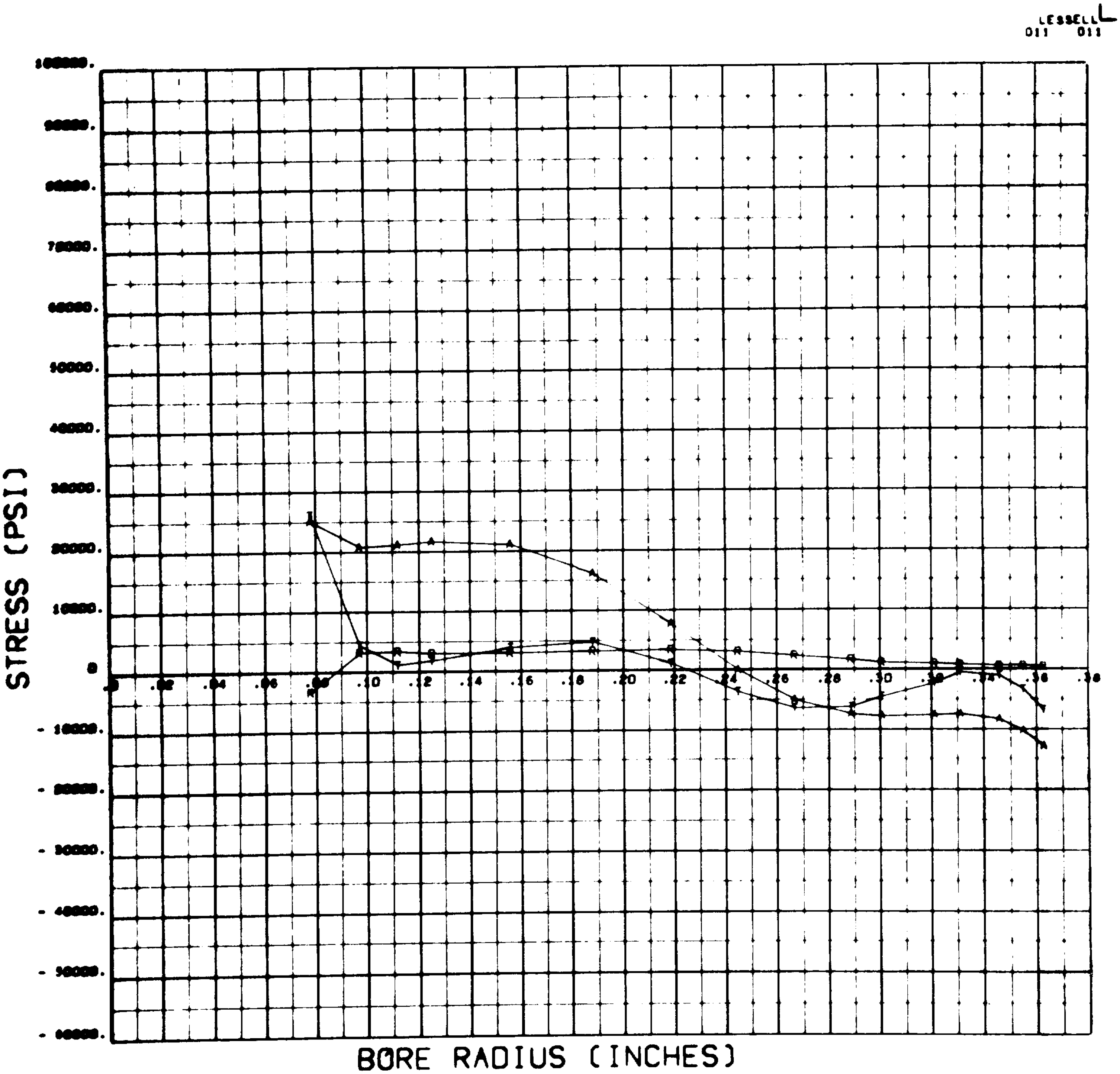
STRESS VS. RADIUS - SPECIMEN B8-3/4



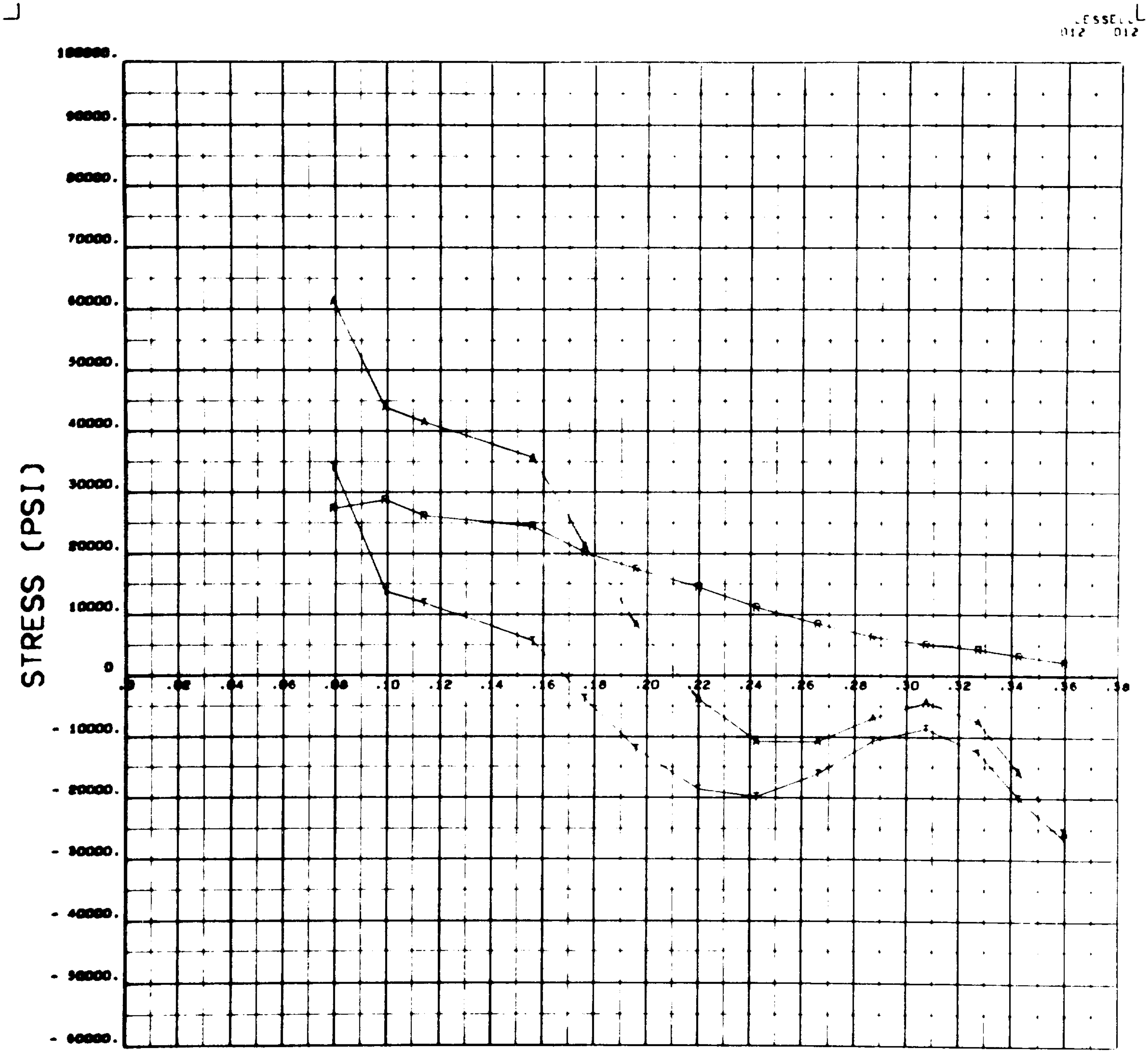
STRESS VS. RADIUS - SPECIMEN B9-3/4



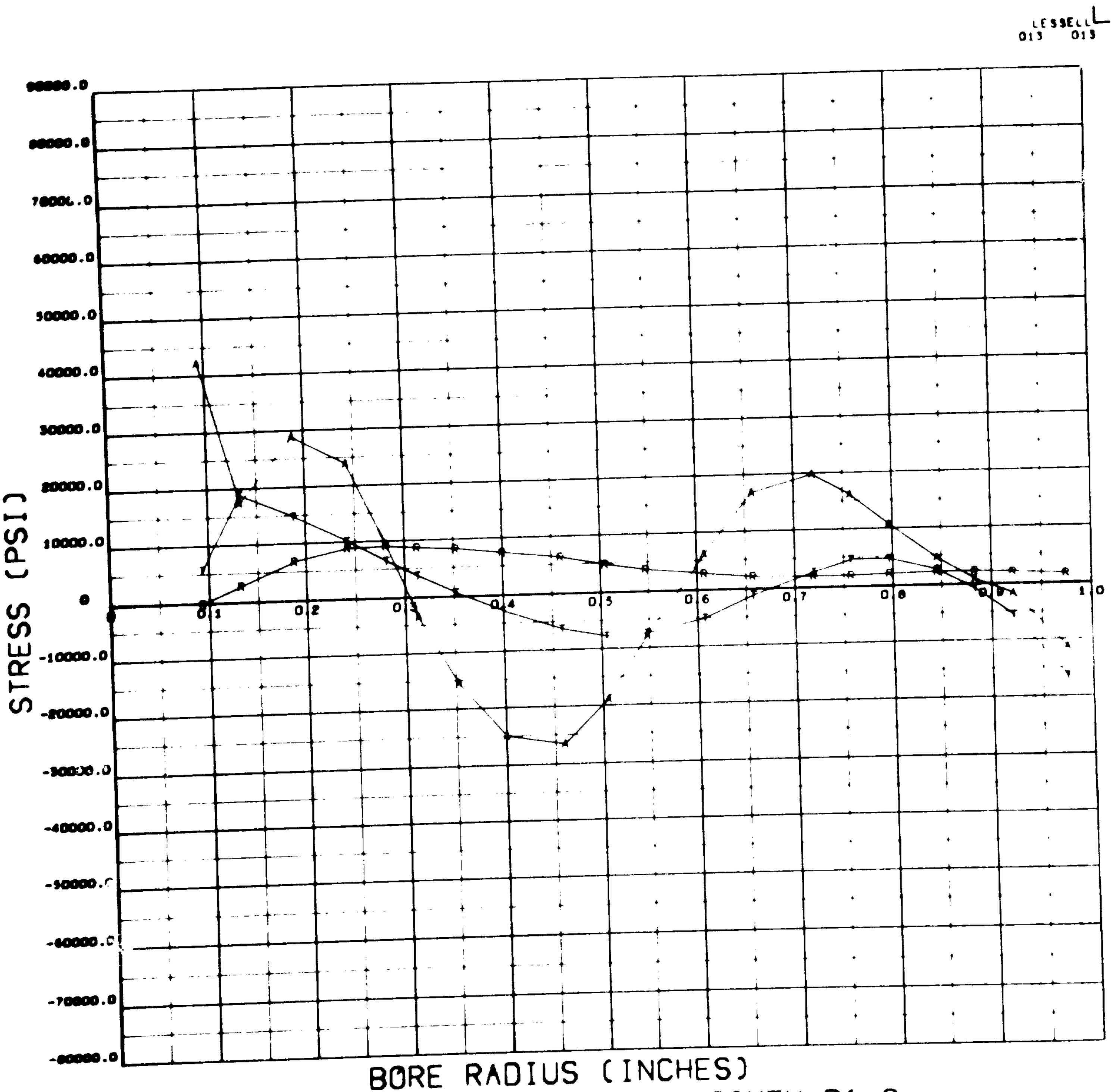
STRESS VS. RADIUS - SPECIMEN B10-3/4



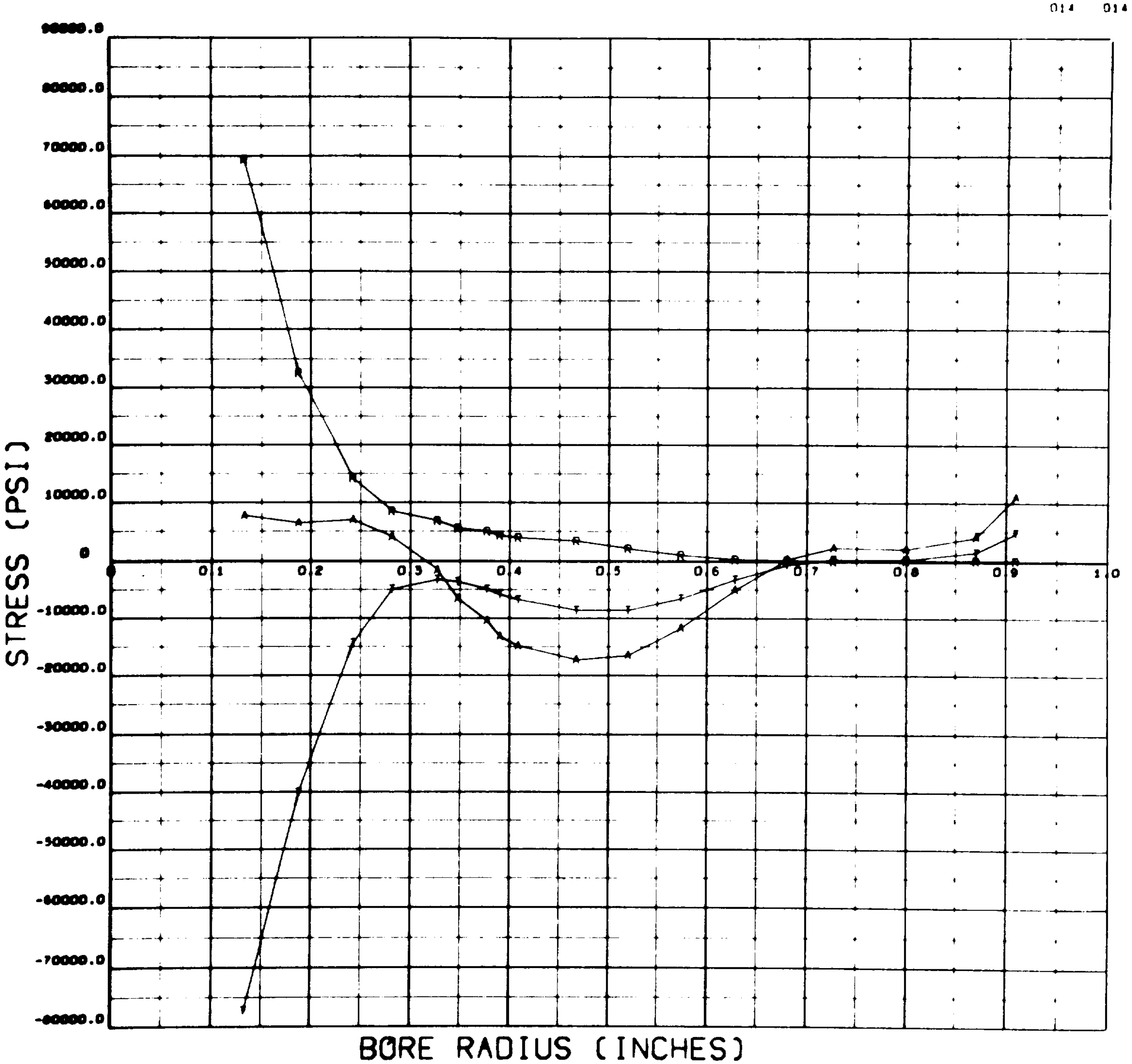
STRESS VS. RADIUS - SPECIMEN B12-3/4



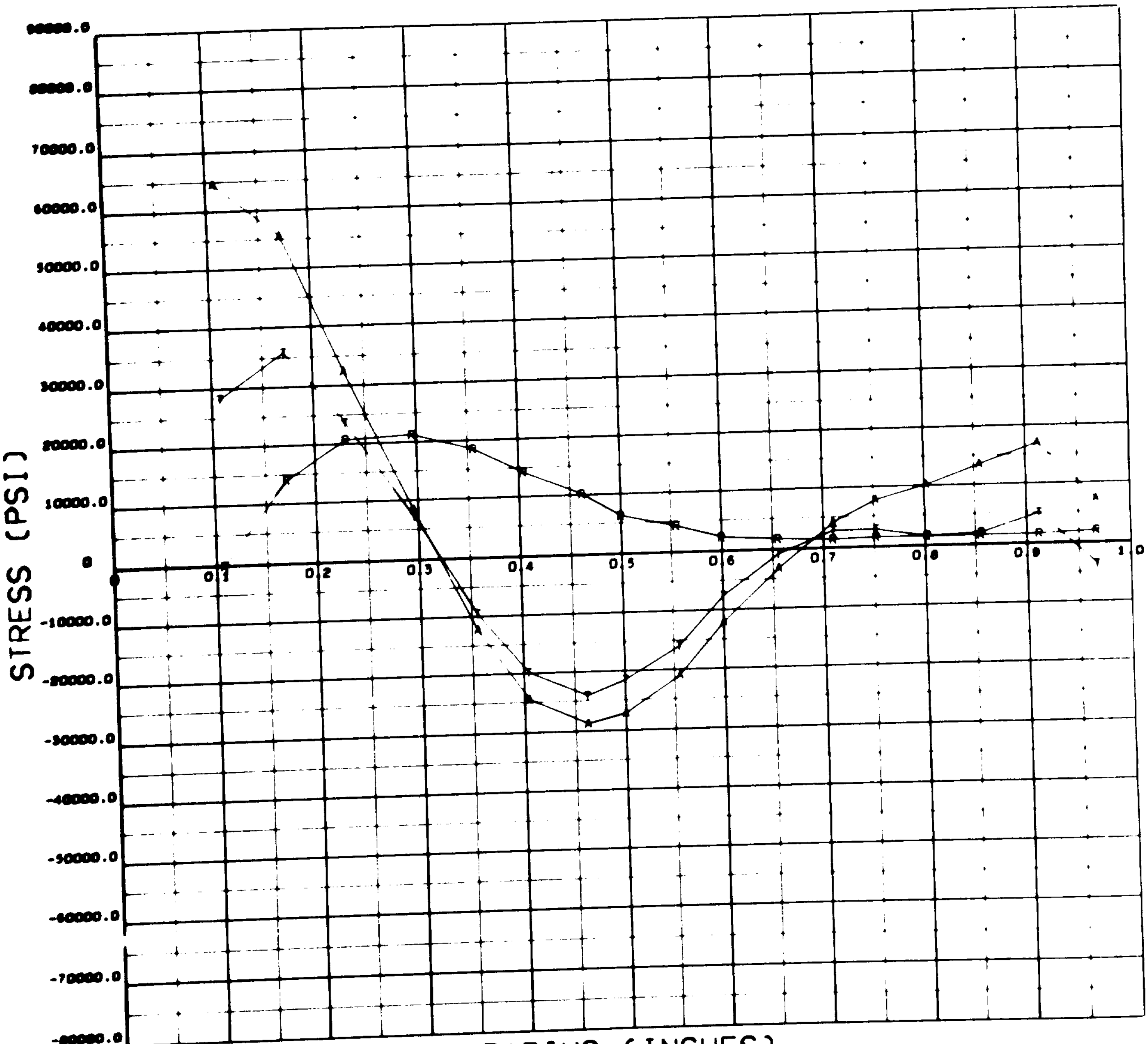
STRESS VS. RADIUS - SPECIEMN B13-3/4



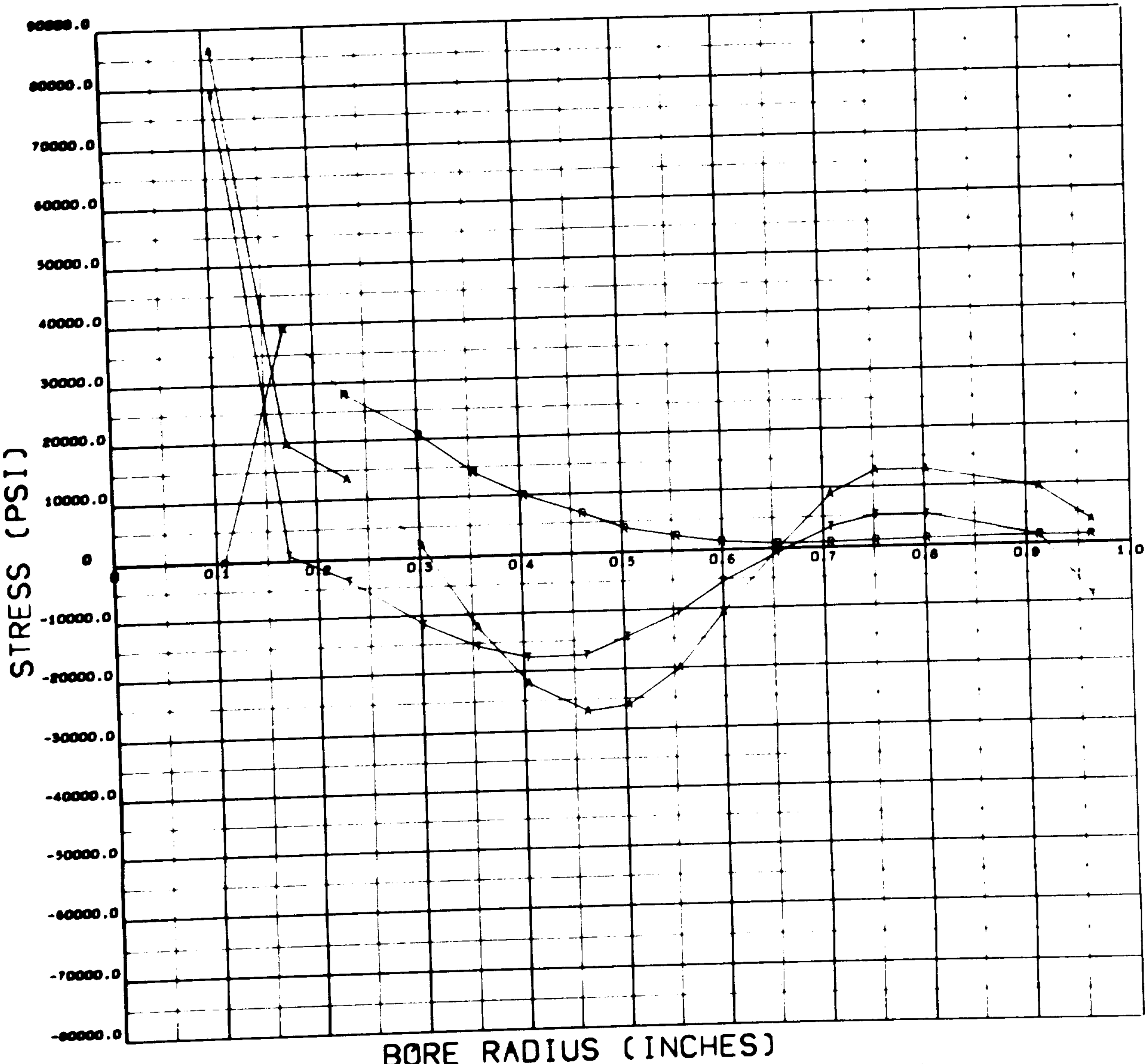
STRESS VS. RADIUS - SPECIMEN B1-2



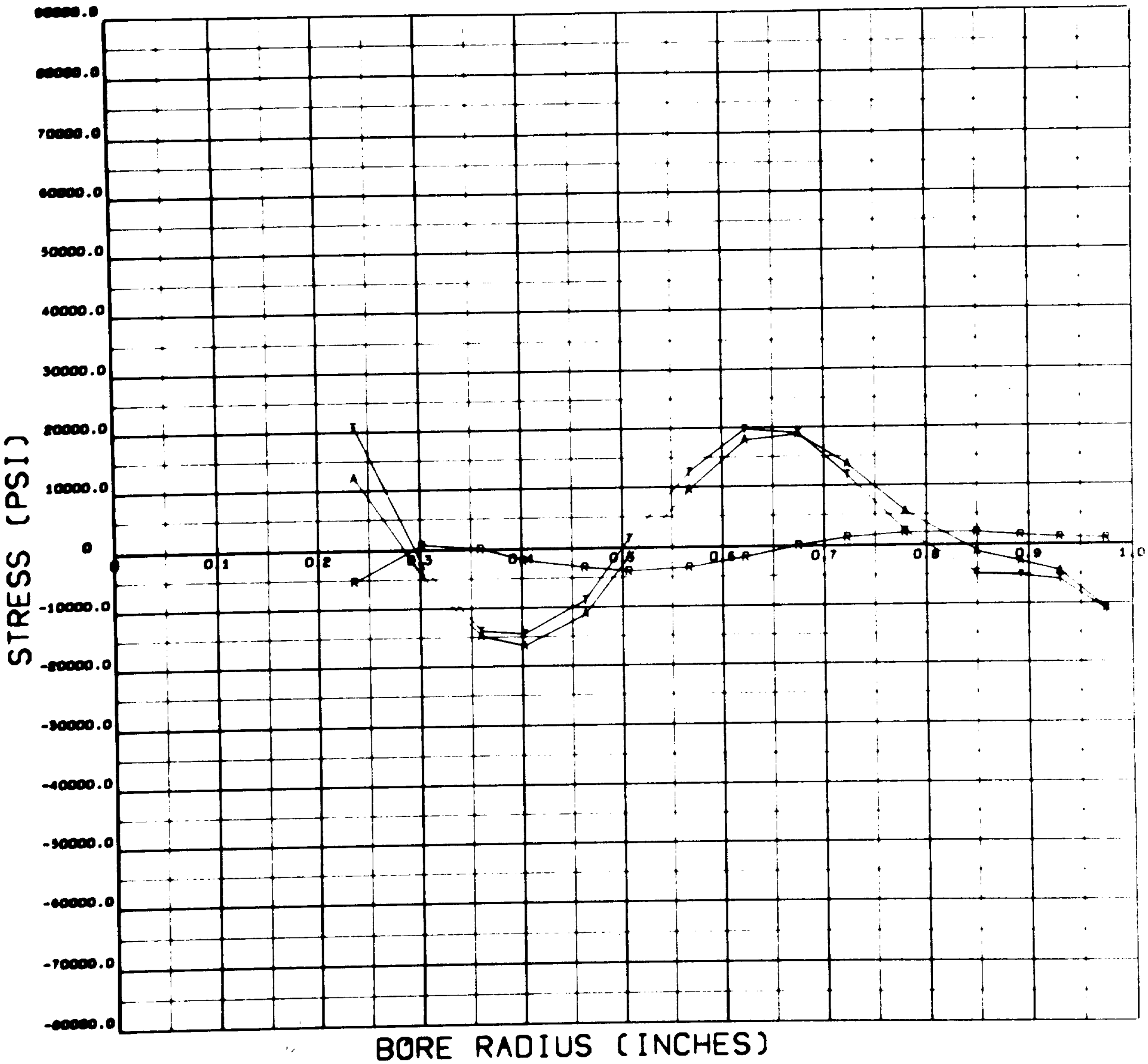
STRESS VS. RADIUS - SPECIMEN B2-2



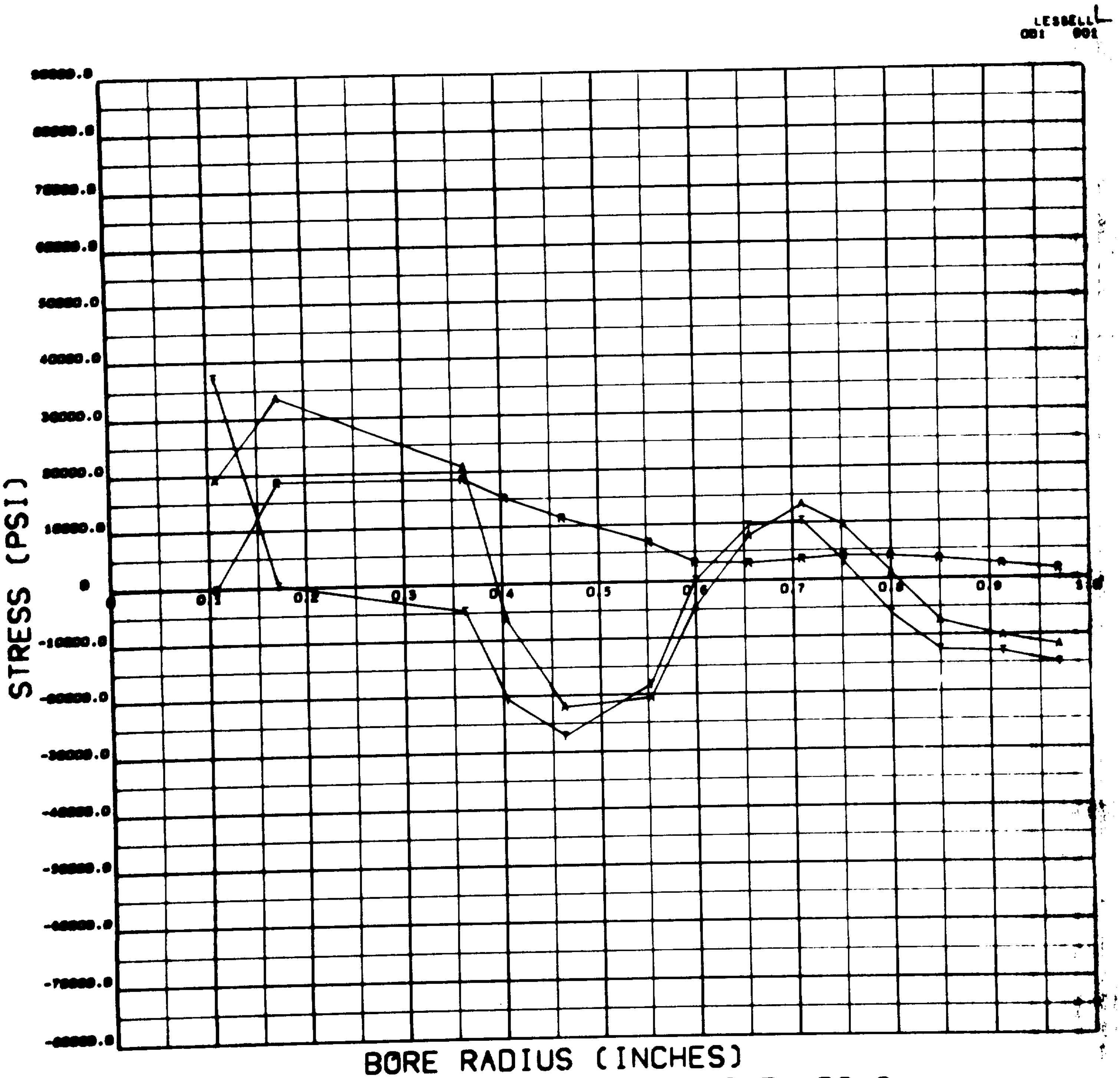
STRESS VS. RADIUS - SPECIMEN B3-2



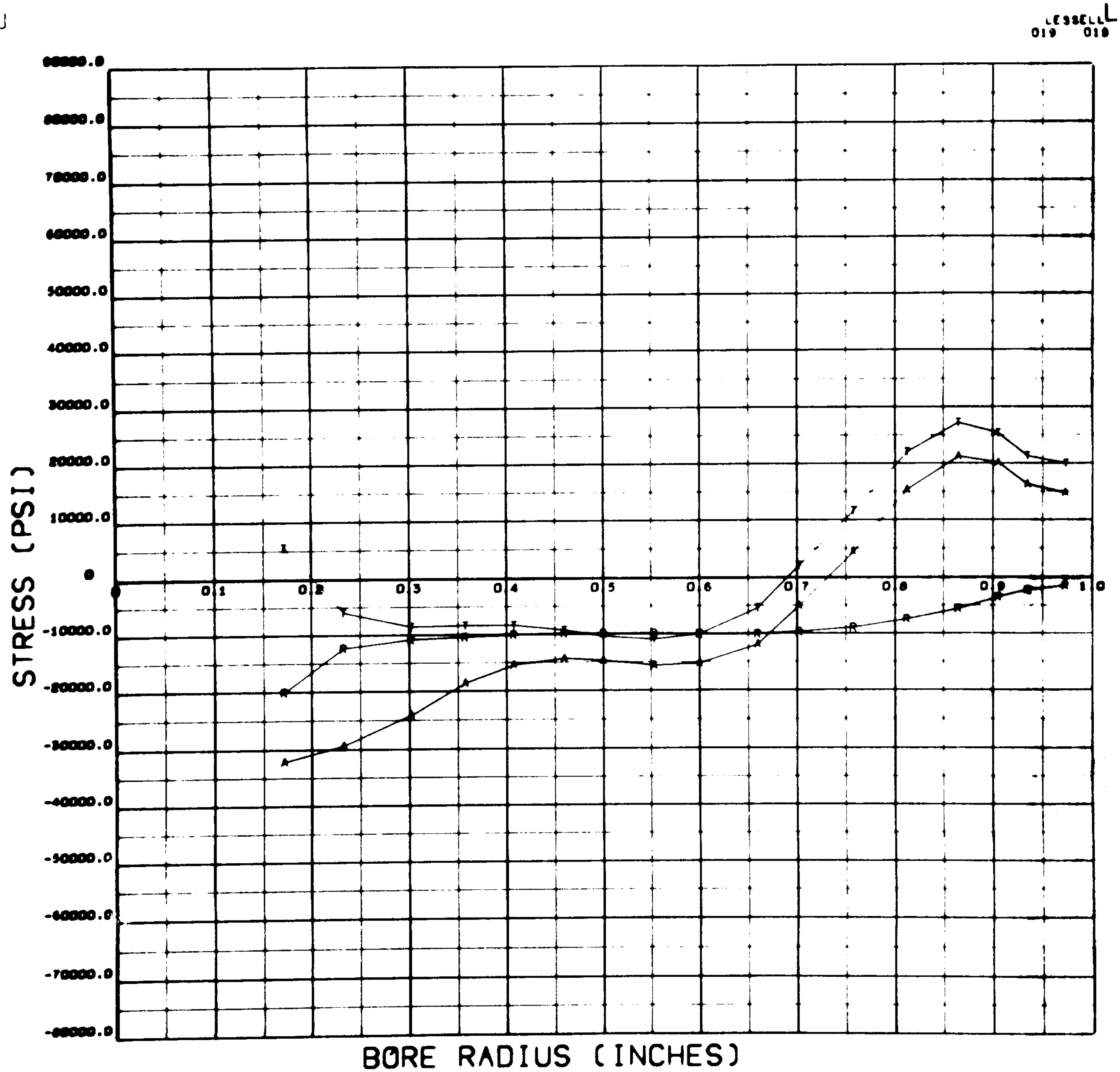
STRESS VS. RADIUS - SPECIMEN B4-2



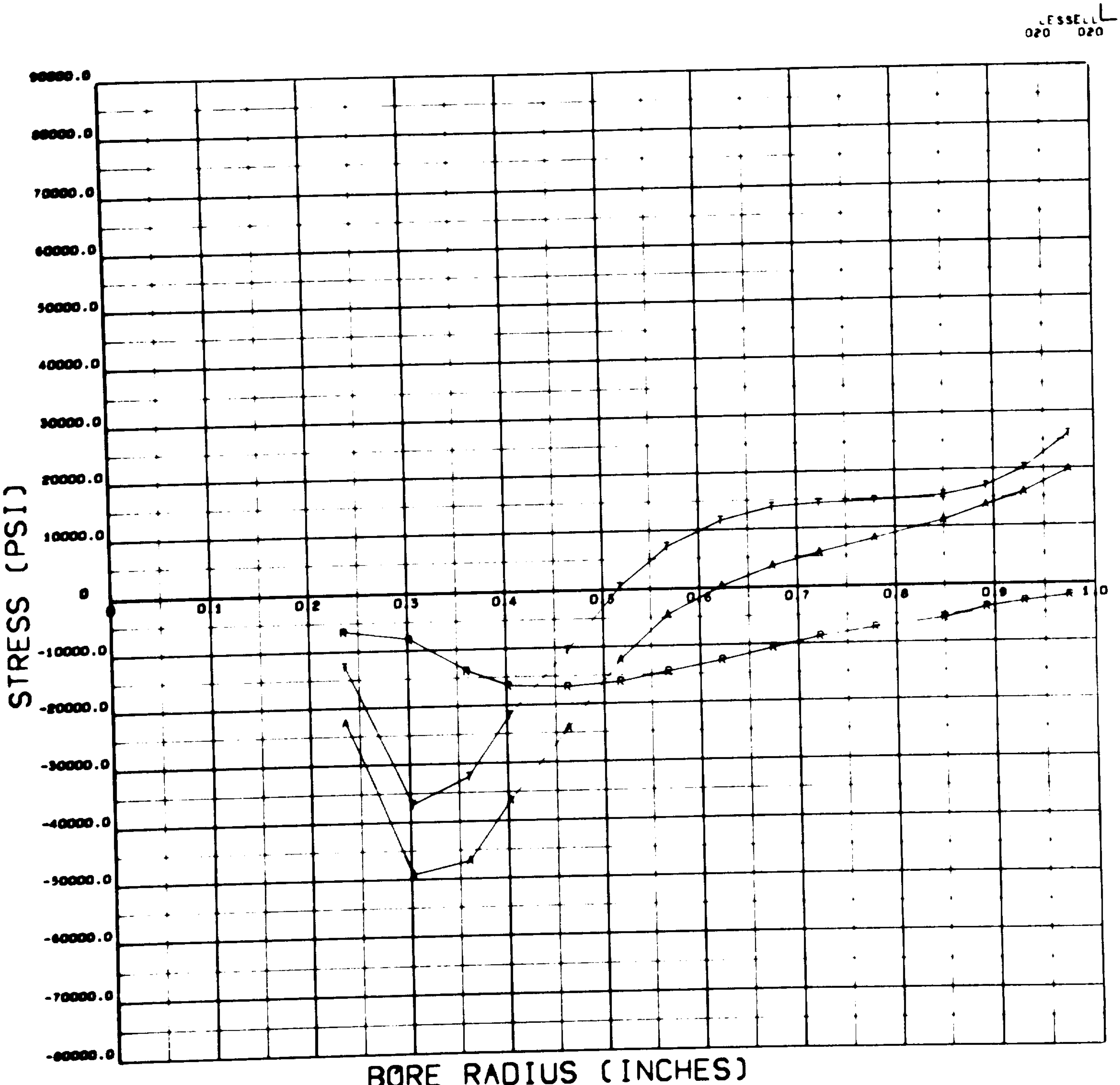
STRESS VS. RADIUS - SPECIMEN B5-2



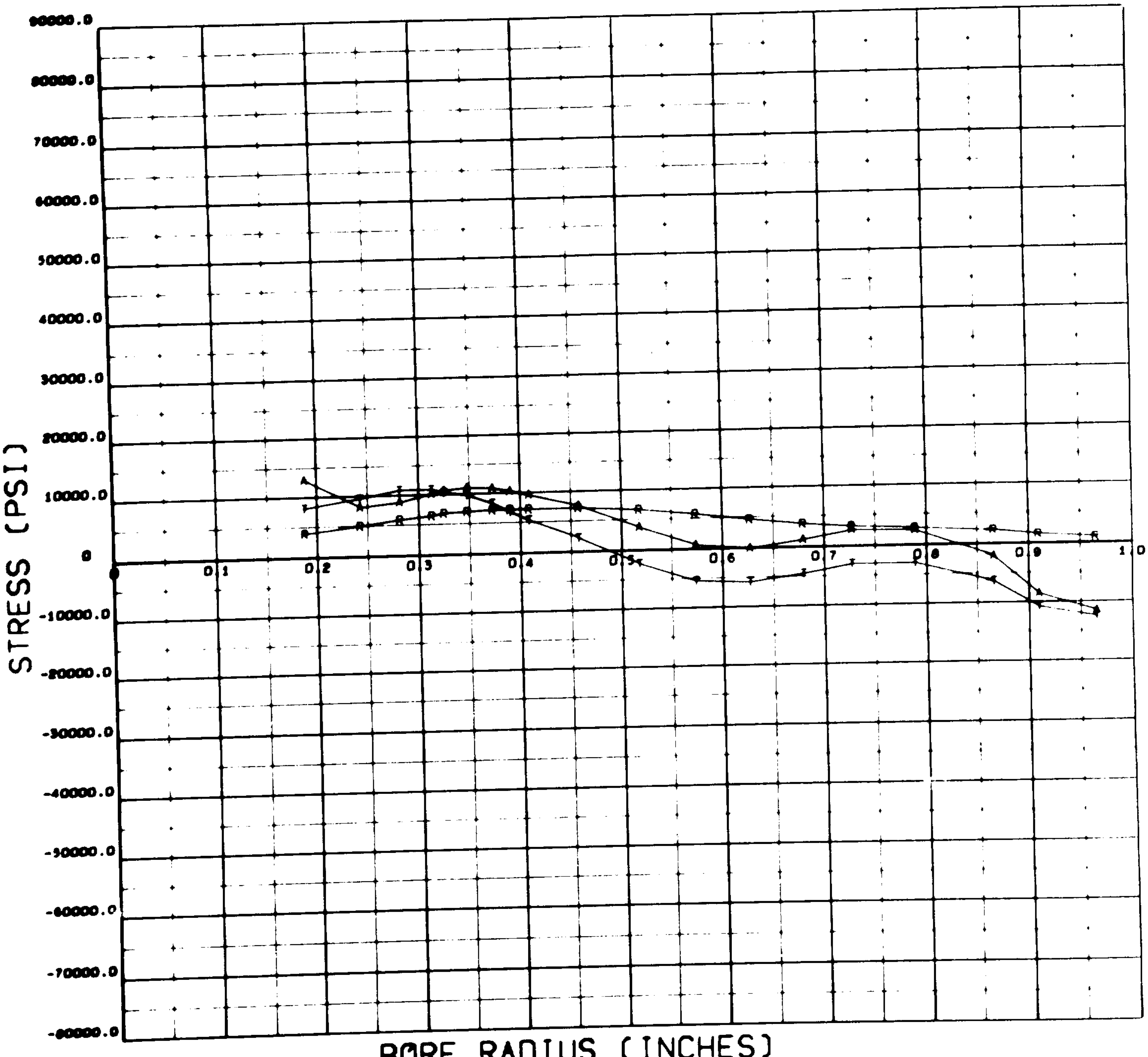
STRESS VS. RADIUS - SPECIMEN B6-2



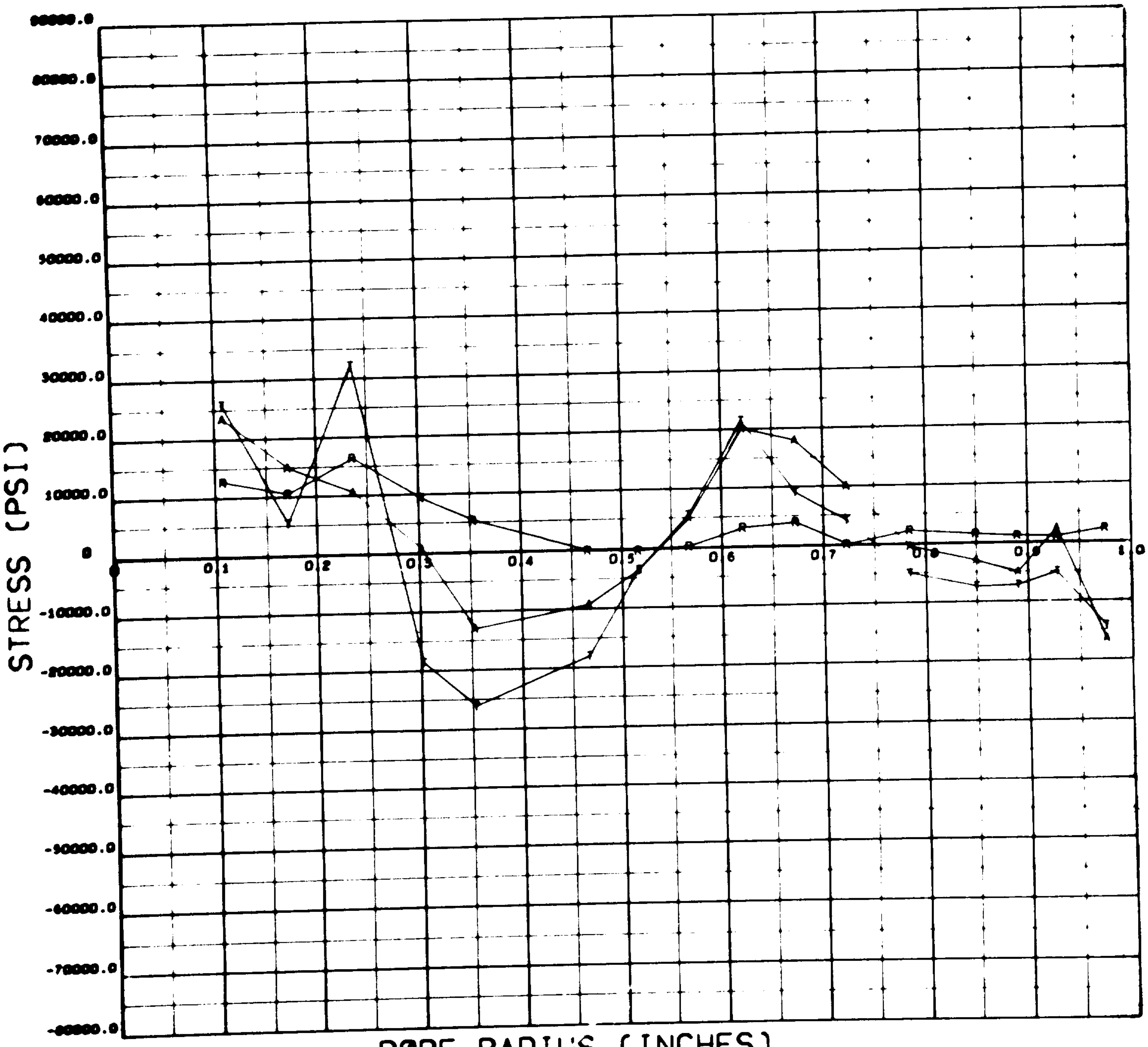
STRESS VS. RADIUS - SPECIMEN B7-2



STRESS VS. RADIUS - SPECIEMN B8-2

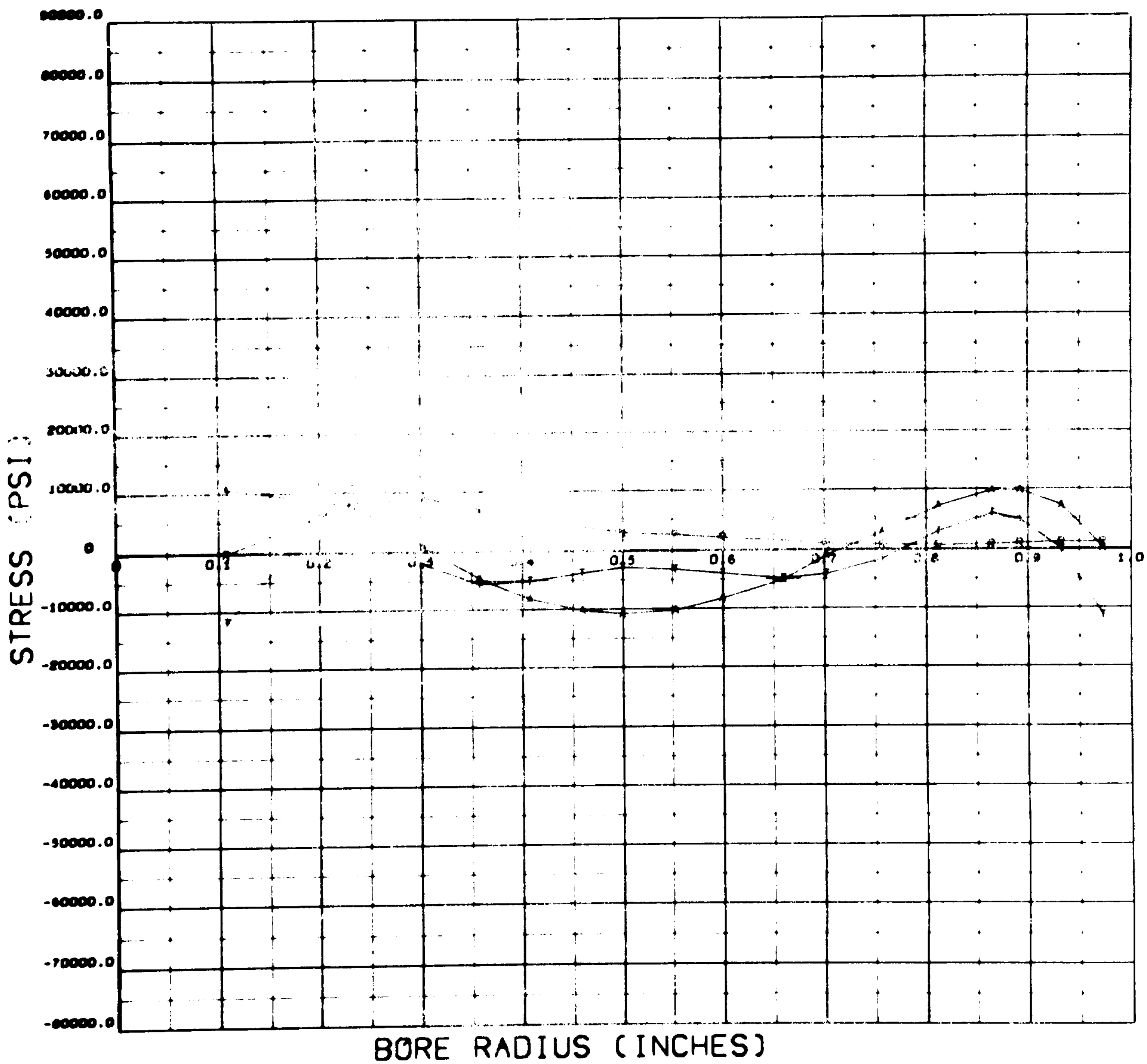


STRESS VS. RADIUS - SPECIMEN B9-2

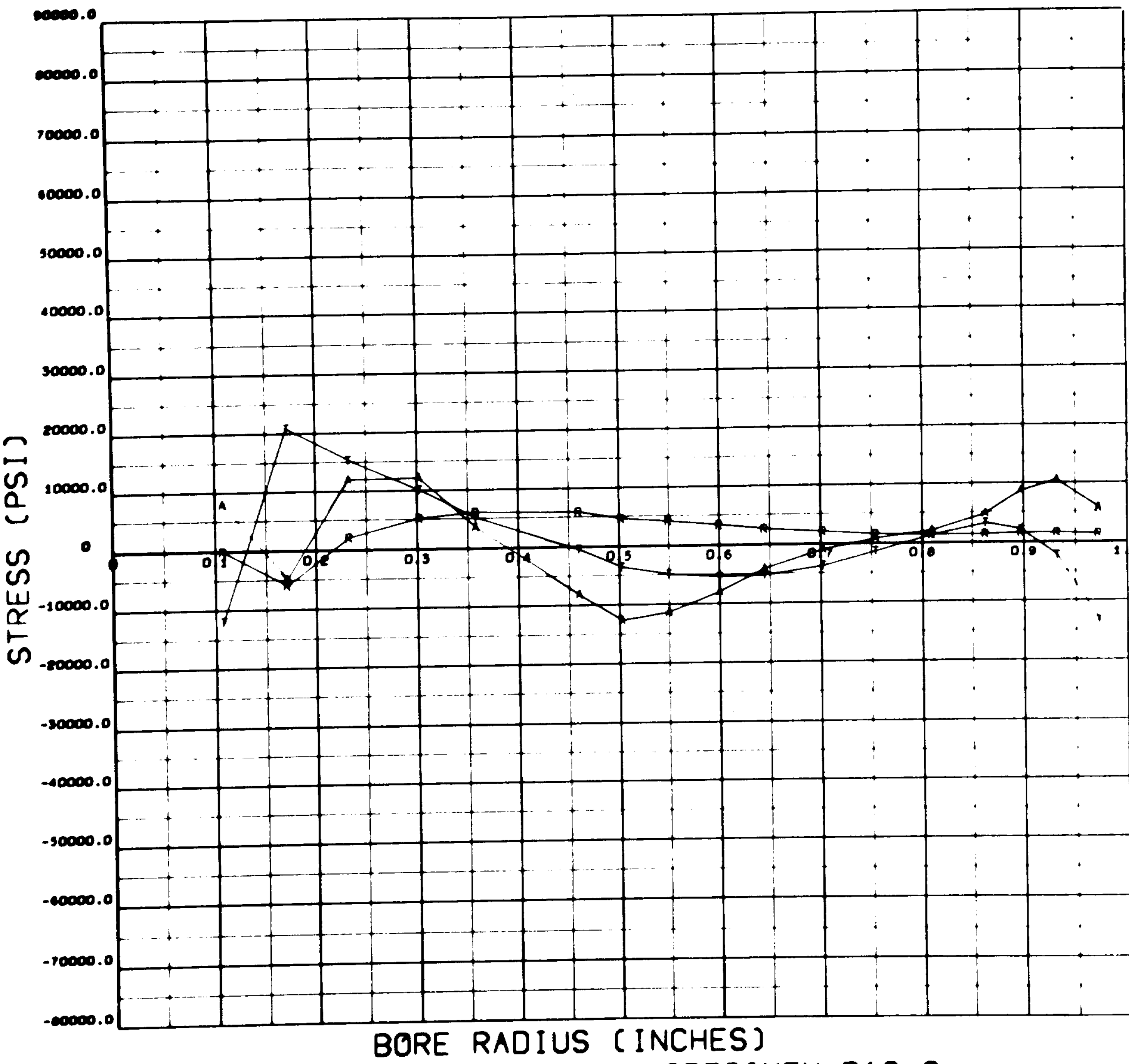


BORE RADIUS (INCHES)

STRESS VS. RADIUS - SPECIMEN B10-2



STRESS VS. RADIUS - SPECIEMN B11-2



STRESS VS. RADIUS - SPECIMEN B12-2

APPENDIX B

STABILITY DATA

Code for Dimensions

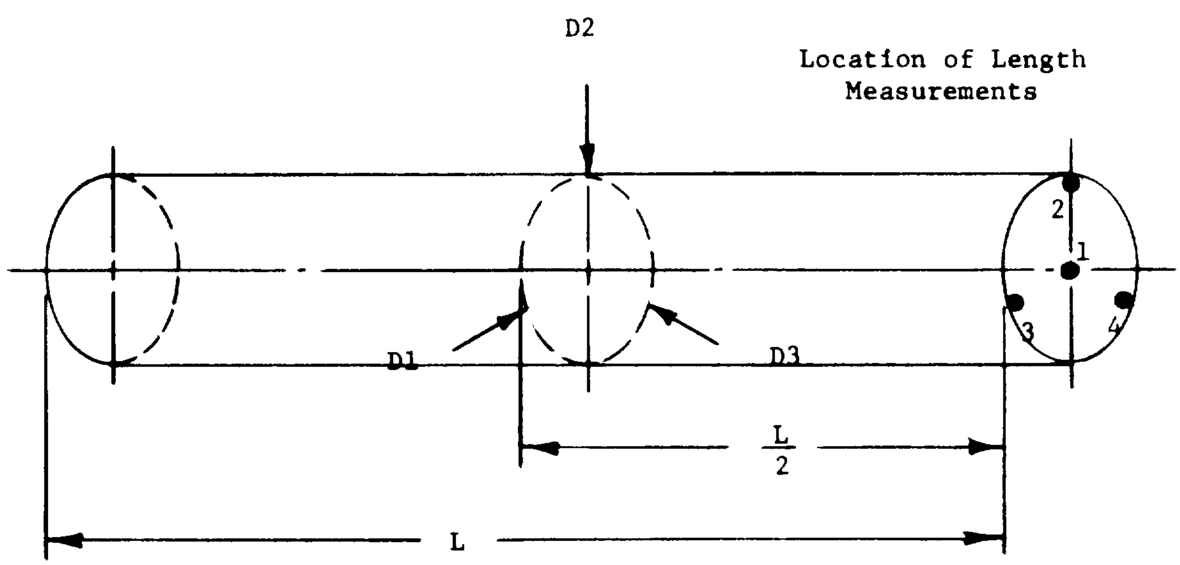


TABLE B-1

STABILITY DATA - 3/4-INCH SPECIMENS

Date	D1	D2	D3	L1	L2	L3	L4	T.I.R.	Notes
Specimen S1 - 3/4	As received								
3-4-65	.75080	.75080	.75080	3.75095	3.75098	3.75087	3.75102	.00120	
3-25-65	.75087	.75087	.75087	3.75117	3.75112	3.75108	3.75124	.00125	
4-20-65	.75086	.75087	.75091	3.75107	3.75112	3.75098	3.75115	.00125	
5-12-65	.75086	.75080	.75088	3.75073	3.75078	3.75065	3.75082	.00125	
6-18-65	.75079	.75078	.75083	3.75098	3.75103	3.75093	3.75108	.00125	
7-14-65	.75078	.75081	.75084	3.75100	3.75108	3.75058	3.75108	.00124	
8-5-65	.75080	.75080	.75085	3.75098	3.75100	3.75090	3.75105	.00124	
8-19-65	.75080	.75078	.75083	3.75097	3.75100	3.75088	3.75105	.00123	
9-3-65	.75080	.75079	.75083	3.75097	3.75105	3.75089	3.75105	.00122	
9-29-65	.75083	.75080	.75083	3.75100	3.75104	3.75092	3.75106	.00123	
Specimen S2 - 3/4	Re-solution - Air cool								
3-4-65	.75088	.75089	.75087	3.74645	3.74655	3.74655	3.74635	.00065	As received
3-8-65	.75125	.75138	.75115	3.74440	3.74450	3.74430	3.74435	.00061	After re-solution treatment
3-24-65	.75108	.75105	.75100	3.74390	3.74400	3.74390	3.74385	.00061	After polish
4-20-65	.75108	.75090	.75092	3.7436	3.74370	3.74364	3.74360	.00061	
5-12-65	.75100	.75095	.75090	3.74360	3.74373	3.74365	3.74360	.00061	
6-18-65	.75095	.75087	.75084	3.74355	3.74370	3.74360	3.74360	.00055	
7-14-65	.75096	.75087	.75093	3.74380	3.74390	3.74385	3.74380	.00055	
8-5-65	.75095	.75087	.75090	3.74340	3.74380	3.74330	3.74350	.00057	
8-19-65	.75097	.75088	.75090	3.74370	3.74400	3.74380	3.74390	.00056	
9-3-65	.75096	.75088	.75089	3.74390	3.74420	3.74390	3.74380	.00057	
9-29-65	.75098	.75090	.75090	3.74390	3.74400	3.74440	3.74390	.00056	

TABLE B-1 (CONTINUED)

STABILITY DATA - 3/4-INCH SPECIMENS									
Date	**D1**	**D2**	**D3**	**L1**	**L2**	**L3**	**L4**	**T.I.R.**	**Notes**
Specimen S3 - 3/4	**Re-solution - Oil Quench**								
3-4-65	.75088	.75090	.75090	3.75050	3.75055	3.75054	3.75050	.00050	As received
3-24-65	.75133	.75140	.75135	3.74715	3.74725	3.74780	3.74650	.00250	After re-solution treatment and polish
4-20-65	.75128	.75142	.75137	3.74690	3.74692	3.74760	3.74610	.00250	
5-12-65	.75125	.75138	.75127	3.74680	3.74692	3.74760	3.74620	.00240	
6-18-65	.75117	.75140	.75128	3.74676	3.74704	3.74750	3.74616	.00243	
7-14-65	.75123	.75142	.75128	3.74690	3.74725	3.74770	3.74628	.00233	
8-5-65	.75126	.75140	.75126	3.74660	3.74728	3.74765	3.74625	.00234	
8-19-65	.75125	.75140	.75127	3.74700	3.74725	3.74770	3.74630	.00235	
9-3-65	.75125	.75136	.75126	3.74720	3.74735	3.74770	3.74635	.00234	
9-29-65	.75124	.75133	.75126	3.74710	3.74715	3.74770	3.74630	.00235	
Specimen S4 - 3/4	**Re-solution - Air cool - 925H**								
3-4-65	.75100	.75100	.75100	3.74883	3.74888	3.74878	3.74893	.0010	As received
3-25-65	.75103	.75105	.75104	3.74882	3.74887	3.74880	3.74892	.0011	As received
4-20-65	.75107	.75105	.75105	3.74873	3.74879	3.74867	3.74881	.0011	As received
5-5-65	.75150	.75132	.75148	3.74554	3.74571	3.74552	3.74558	.0012	Re-solution, 925H,, not polished
5-12-65	.75135	.75120	.75139	3.74535	3.74560	3.74520	3.74575	.0012	
6-18-65	.75142	.75120	.75129	3.74530	3.74544	3.74512	3.74574	.0015	
7-14-65	.75132	.75119	.75120	3.74550	3.74570	3.74595	3.74594	.0013	
8-5-65	.75129	.75115	.75122	3.74555	3.74575	3.74540	3.74572	.0014	
8-19-65	.75128	.75120	.75121	3.74559	3.74580	3.74554	3.74585	.0014	
9-3-65	.75127	.75119	.75121	3.74560	3.74580	3.74535	3.74595	.0014	
9-29-65	.75124	.75118	.75120	3.74550	3.74570	3.74525	3.74585	.0014	

TABLE B-1 (CONTINUED)

STABILITY DATA - 3/4-INCH SPECIMENS

Date	D1	D2	D3	L1	L2	L3	L4	T.I.R.	Notes
Specimen S5 - 3/4	As received - 1075 harden								
3-2-65	.75165	.75165	.75165	3.74820	3.74815	3.74828	3.74822	.00090	As received
3-25-65	.75170	.75170	.75170	3.74811	3.74806	3.74817	3.74816	.00085	As received
4-20-65	.75171	.75171	.75172	3.74795	3.74791	3.74803	3.74800	.00082	As received
5-12-65	.75130	.75131	.75130	3.74790	3.74835	3.74790	3.74755	.00077	After 1075 harden
6-18-65	.75120	.75123	.75126	3.74770	3.74810	3.74780	3.74720	.00079	
7-14-65	.75130	.75122	.75127	3.74730	3.74680	3.74665	3.74670	.00080	
8-5-65	.75120	.75125	.75124	3.74728	3.74660	3.74640	3.74637	.00079	
8-19-65	.75123	.75124	.75124	3.74680	3.74660	3.74650	3.74652	.00079	
9-3-65	.75122	.75123	.75123	3.74660	3.74660	3.74660	3.74654	.00080	
9-29-65	.75123	.75124	.75124	3.74640	3.74655	3.74660	3.74640	.00080	

TABLE B-2

STABILITY DATA - 2-INCH SPECIMENS

Date	D1	D2	D3	L1	L2	L3	L4	T.I.R.	Notes
Specimen S1 - 2	**As received**								
3-2-65	1.9995	1.9989	1.99900	10.2144	9.9995	9.9992	9.9976	.00020	
3-25-65	1.9990	1.9978	1.99905	10.2144	9.9995	9.9992	9.9997	.00030	
4-23-65	1.9988	1.9990	1.9987	10.2146	9.9995	9.9990	9.9997	.00025	
5-12-65	1.9980	1.9980	1.9987	10.2145	9.9995	9.9993	9.9997	.00027	
6-18-65	1.9980	1.9983	1.9988	10.2144	9.9995	9.9992	9.9996	.00027	
7-14-65	1.9980	1.9990	1.9989	10.2141	9.9994	9.9991	9.9996	.00025	
8-5-65	1.9980	1.9989	1.9989	10.2142	9.9995	9.9990	9.9995	.00026	
8-19-65	1.9981	1.9988	1.9989	10.2142	9.9995	9.9991	9.9994	.00025	
9-3-65	1.9982	1.9989	1.9989	10.2142	9.9995	9.9992	9.9994	.00025	
9-29-65	1.9986	1.9989	1.9989	10.2143	9.9995	9.9990	9.9994	.00026	
Specimen S2 - 2	**Re-solution - Air cool**								
3-4-65	2.00050	2.00000	2.0015	10.0075	9.9935	9.9945	9.9945	.00035	As received
3-26-65	2.00302	1.99895	2.0014	10.0009	9.9836	9.9853	9.9853	.00210	After re-solution treatment
4-23-65	2.00260	2.00080	1.9989	9.9987	9.9835	9.9855	9.9853	.00270	
5-12-65	2.00270	2.00090	1.9982	9.9987	9.9833	9.9858	9.9852	.00270	
6-18-65	2.00270	2.00145	1.9983	9.9987	9.9838	9.9858	9.9853	.00272	
7-14-65	2.00270	2.00140	1.9980	9.9989	9.9837	9.9853	9.9850	.00271	
8-5-65	2.00270	2.00137	1.9984	9.9989	9.9834	9.9856	9.9849	.00271	
8-19-65	2.00268	2.00138	1.9989	9.9989	9.9840	9.9855	9.9850	.00270	
9-3-65	2.00266	2.00137	1.9987	9.9988	9.9860	9.9856	9.9850	.00270	
9-29-65	2.00265	2.00137	1.9988	9.9989	9.9840	9.9855	9.9850	.00265	

TABLE B-2 (CONTINUED)

STABILITY DATA - 2-INCH SPECIMENS

Date	D1	D2	D3	L1	L2	L3	L4	T.I.R.	Notes
Specimen S3 - 2	Re-solution - oil quench								
3-2-65	2.0007	2.0004	2.0006	10.0092	10.0034	10.0031	10.0032	.0003	As received
3-26-65	2.0013	2.0018	2.00343	10.0012	9.9942	9.9896	9.9896	.0057	After re-solution treatment
4-23-65	2.0021	2.0028	2.00230	10.0018	9.9943	9.9892	9.9883	.0057	
5-12-65	2.0021	2.0031	2.00190	10.0012	9.9940	9.9893	9.9882	.0056	
6-18-65	2.0022	2.0031	2.00140	10.0011	9.9943	9.9892	9.9882	.0052	
7-14-65	2.0021	2.0029	2.00140	10.0011	9.9942	9.9893	9.9897	.0052	
8-5-65	2.0021	2.0031	2.00140	10.0011	9.9943	9.9892	9.9880	.0052	
8-19-65	2.0020	2.0031	2.00139	10.0011	9.9942	9.9895	9.9880	.0053	
9-3-65	2.0021	2.0031	2.00138	10.0012	9.9940	9.9900	9.9880	.0052	
9-29-65	2.0021	2.0031	2.00140	10.0013	9.9939	9.9890	9.9880	.0052	
Specimen S4 - 2	Re-solution - Air cool - 925H								
3-2-65	2.00048	2.00040	2.00050	10.2083	10.0030	10.0032	10.0036	.0003	As received
3-25-65	2.00058	2.00037	2.00042	10.2081	10.0033	10.0032	10.0035	.0003	As received
4-23-65	2.00057	2.0037	2.00041	10.2076* 10.0150	10.0033	10.0033	10.0034	.0004	*Ground off center projection
5-5-65	2.00087	2.00105	2.00005	10.00440	9.9941	9.9922	9.9933	.0033	After re-solution treatment
5-12-65	2.00087	2.00105	2.00000	10.00450	9.9937	9.9917	9.9920	.0033	
6-18-65	2.00083	2.00100	2.00005	10.00350	9.9943	9.9922	9.9922	.0033	
7-14-65	2.00084	2.00100	2.00005	10.00391	9.9944	9.9920	9.9932	.0033	
8-5-65	2.00083	2.00100	2.00005	10.00391	9.9936	9.9920	9.9933	.0033	
8-19-65	2.00084	2.00098	2.00005	10.00400	9.9932	9.9918	9.9932	.0033	
9-3-65	2.00083	2.00099	2.00000	10.00400	9.9931	9.9918	9.9935	.0033	
9-29-65	2.00083	2.00097	2.00000	10.00392	9.9930	9.9920	9.9934	.0033	

TABLE B-2 (CONTINUED)

STABILITY DATA ---, 2-INCH SPECIMENS

Date	D1	D2	D3	L1	L2	L3	L4	T.I.R.	Notes
Specimen S4 - 2	As received - 1075H								
3-2-65	2.0000	2.0001	2.00025	10.2041	10.0024	10.0028	10.0027	.0004	As received
3-25-65	2.0001	2.0001	2.00020	10.2043	10.0025	10.0026	10.0027	.0004	As received
4-23-65	2.0000	2.0002	2.00015	10.2042	10.0022	10.0024	10.0028	.0004	
5-12-65	1.9988	1.9985	1.9986	10.0114	9.9975	9.9972	9.9970	.0004	After 1075 and grind off center projection
6-18-65	1.9987	1.9986	1.9989	10.0114	9.9968	9.9972	9.9970	.0004	
7-14-65	1.9987	1.9986	1.9989	10.0114	9.9968	9.9971	9.9970	.0004	
8-5-65	1.9988	1.9990	1.9990	10.0113	9.9967	9.9970	9.9971	.0004	
8-19-65	1.9988	1.9989	1.9990	10.0113	9.9970	9.9972	9.9970	.0004	
9-3-65	1.9987	1.9990	1.9990	10.0112	9.9968	9.9976	9.9969	.0004	
9-29-65	1.9988	1.9990	1.9991	10.0113	9.9972	9.9978	9.9970	.0004	

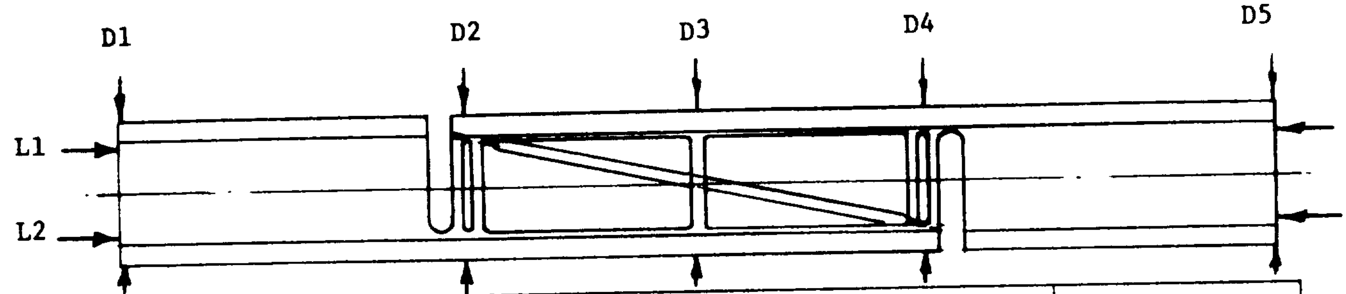
APPENDIX C

SIMULATED AXIAL SECTION DATA

TABLE C-1

LENGTH AND VERTICAL DIAMETER CHANGES

Code for Dimensions



Specimen	Condition[1]	D1	D2	D3	D4	D5	L1	L2
A1	925H	-3[2]	-3	-4	-3	-4	-20	-25
	Free	-3	-3	-4	-4	-4	-23	-22
A2	925H	-3	-5	-3	-4	-3	-25	-34
	Free	-4	-1	+3	-4	-2	-26	-34
A3	1900 Re-s	+3	0	-4	0	+1	-68	-80
	925H	+1	-1	-5	-2	+4	-98	-92
	Free	+1	-6	-16	-6	+4	-108	-99
A4	1900 Re-s	+7	-1	-5	0	+10	-92	-104
	925H	+2	-5	-5	-2	+8	-112	-120
	Free	+2	-7	-15	-5	+8	-112	-121
A5	Free	—	—	—	—	—	-9	-7
	925H	0	-1	-2	-3	-1	-37	-28
A6	Free	0	+1	+9	0	+1	-5	0
	925H	-4	0	+8	-2	-1	-15	-23
A7	Free	—	—	—	—	—	-5	-7
	1900 Re-s	0	-1	-2	-4	+8	-60	-84
	925H	0	-3	-2	-7	+7	-73	-107
A8	Free	0	+2	+13	0	0	0	-5
	1900 Re-s	+9	-3	+4	-5	+14	-83	-65
	925H	+7	-4	+8	-5	+9	-97	-69
A9	Free	+1	+7	+20	+6	0	-1	-1
A10	Free	-1	+6	+33	+6	+3	0	0

Notes: 1) All specimens except A9 and A10 were re-solutioned and machined prior to first condition listed. A9 and A10 1075 hardened and machined.

2) Numbers are .0001 inch referred to as-machined condition, e.g., 3 = .0003 inch.

TABLE C-2

CONTOUR DATA

Numbers represent 0.0001 inch deviation from the as-machined condition. Positive numbers represent outward displacement of the face in question.

Face and Station Number Code

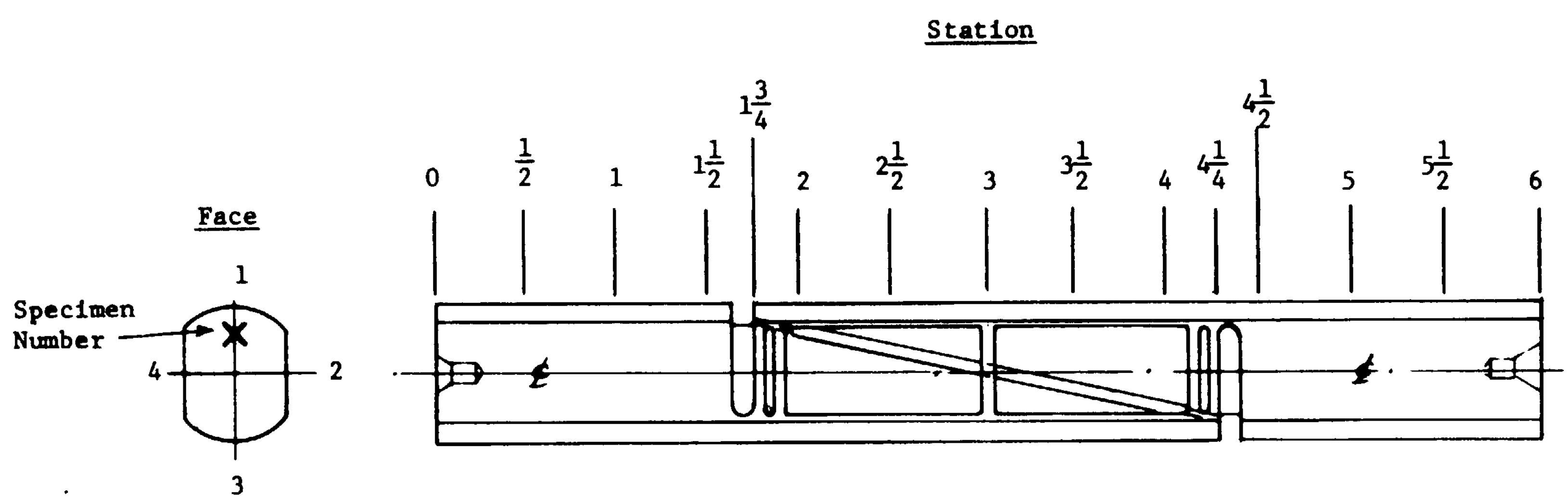


TABLE C-2

CONTOUR DATA

Specimen and Condition	Face	Station Number												
		$\frac{1}{2}$	1	$1\frac{1}{2}$	Flex $1\frac{3}{4}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4	Flex $4\frac{1}{4}$	$4\frac{1}{2}$	5	$5\frac{1}{2}$
A1	1	0	0	0	—	0	-1	+1	0	+1	—	-1	-1	0
925	2	0	0	0	+1	—	—	0	—	—	+1	0	-1	+1
	3	0	+1	0	—	0	+2	-1	+1	+2	—	+1	+1	+1
	4	+5	+3	+3	+2	—	—	0	—	—	-3	-3	-4	-4
Gaged	1	-1	-1	-1	—	-2	-2	-2	-2	-2	—	-3	-1	-1
and	2	0	+1	+1	+1	—	—	-2	—	—	-2	-1	-1	0
Free	3	0	+2	+2	—	+2	+2	+2	+3	+3	—	+1	+2	+2
	4	+5	+3	+3	0	—	—	+1	—	—	+1	0	-1	-1
A2	1	+3	+3	+4	—	+6	+2	-3	-8	-11	—	-10	-8	-4
925H	2	0	+1	+2	+1	—	—	+1	—	—	+1	0	0	0
	3	-3	-2	-3	—	-12	-12	-6	-2	+2	—	+1	+4	-1
	4	-1	-1	-1	-1	—	—	0	—	—	+1	+1	+1	+1
Gaged	1	0	-2	-4	—	-2	+1	-1	0	+2	—	-1	+1	+3
and	2	+1	+2	+4	+4	—	—	0	—	—	+1	0	0	+1
Free	3	+1	+2	+2	—	+3	+3	+4	+1	-1	—	-2	-1	-4
	4	0	-1	-1	-4	—	—	-1	—	—	+1	0	+1	0

TABLE C-2 (CONTINUED)

CONTOUR DATA

Specimen and Condition	Face	Station Number $\frac{1}{2}$	1	$1\frac{1}{2}$	Flex $1\frac{3}{4}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4	Flex $4\frac{1}{4}$	$4\frac{1}{2}$	5	$5\frac{1}{2}$
A3 1900 Re-S	1	+1	+1	0	—	+3	+1	-4	-8	-7	—	-8	-4	-1
	2	-5	-11	-17	-26	—	—	-22	—	—	-21	-15	-5	-1
	3	+1	+3	+2	—	+3	+2	+3	+5	+3	—	+3	+3	0
	4	+10	+15	+21	+22	—	—	+28	—	—	+16	+15	+1	+9
925H	1	0	0	0	—	+1	+1	-4	-8	-7	—	-6	-3	-3
	2	0	-15	-19	-32	—	—	-1	—	—	-26	-24	-14	-8
	3	0	+1	+3	—	+2	+2	+3	+6	+4	—	+3	+3	+3
	4	+10	+17	+25	+26	—	—	+35	—	—	+21	+18	+22	+11
Gaged and Free	1	+1	+1	+1	—	+1	-2	-9	-12	-12	—	-10	-6	-2
	2	-7	-14	-20	-30	—	—	-27	—	—	-24	-17	-12	-5
	3	0	+2	+3	—	+1	0	-1	0	0	—	+4	+5	+3
	4	+10	+17	+27	+27	—	—	+36	—	—	+20	+20	+14	+7
A4 1900 Re-S	1	+5	+7	+10	—	+9	+6	+4	+2	+1	—	+1	+1	+2
	2	+3	+7	+12	+8	—	—	+20	—	—	+11	+15	+11	+9
	3	+3	+1	-7	—	-12	-8	-7	-10	-8	—	-1	0	+1
	4	-3	-8	-13	-22	—	—	-25	—	—	-21	-13	-7	-3
925H	1	+6	+10	+12	—	+9	+6	+6	+2	+2	—	+2	+3	+3
	2	+9	+15	+20	+17	—	—	+31	—	—	+19	+23	+17	+11
	3	-1	-4	-8		-13	-9	-7	-11	-8		-4	0	-1
	4	-4	-8	-15	-27	—	—	-35	—	—	-27	-17	-10	-4
Gaged and Free	1	+4	+10	+11	—	+7	+3	0	-2	-2	—	+2	+4	+5
	2	+7	+11	+18	+16	—	—	+29	—	—	+19	+21	+19	+11
	3	-2	-4	-8	—	-13	-13	-16	-15	-8	—	-4	-1	0
	4	-3	-9	-15	-27	—	—	-36	—	—	-24	-20	-11	-6

TABLE C-2 (CONTINUED)

CONTOUR DATA

Specimen and Condition	Face	Station Number												
					Flex						Flex			
		$\frac{1}{2}$	1	$1\frac{1}{2}$	$1\frac{3}{4}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4	$4\frac{1}{4}$	$4\frac{1}{2}$	5	$5\frac{1}{2}$
A5 Gaged and Free	1	0	-1	+2	—	+2	+6	+5	+7	+5	—	+4	+5	+2
	2	+1	+1	+3	+8	—	—	-2	—	—	-5	-1	-1	0
	3	0	-1	-1	—	+2	-1	-2	-1	-3	—	-3	-3	-1
	4*	—	—	—	—	—	—	—	—	—	—	—	—	—
925H	1	+1	-1	+1	—	+3	+4	+2	+4	+4	—	—	+3	+2
	2	0	-2	+1	+16	—	—	-8	—	—	-10	-10	-12	-14
	3	0	+1	+1	—	+1	-2	-2	-2	-2	—	-3	-2	-1
	4*	+14	-2	-4	+6	—	—	-8	—	—	+3	-10	-9	-10
	*	No zero readings on as-machined specimen - Δ's taken between the two specimen conditions.												
A6 Gaged and Free	1	-1	-1	-4	—	-4	-1	+2	+3	+2	—	+3	+3	0
	2	+9	-3	-3	0	—	—	+2	—	—	+3	-9	-7	-11
	3	+3	+5	+8	—	+8	+11	+9	+10	+2	—	-3	-2	-1
	4	+15	0	-2	+5	—	—	-7	—	—	0	-11	-12	-13
925H	1	-1	-4	-6	—	-5	0	+1	+2	+1	—	+1	+1	0
	2	0	-1	0	0	—	—	0	—	—	-1	-1	+1	+1
	3	+2	+4	+7	—	+6	+9	+8	+8	+3	—	-4	-4	-2
	4	0	-2	0	+1	—	—	-2	—	—	-4	-2	-2	-2

TABLE C-2 (CONTINUED)

CONTOUR DATA

Specimen and Condition	Face	Station Number 1/2	1	1 1/2	Flex 1 3/4	2	2 1/2	3	3 1/2	4	Flex 4 1/4	4 1/2	5	5 1/2
A7 Gaged and Free	1	0	0	+3	—	0	0	-1	-1	-2	—	-6	-4	+1
	2	0	+4	+3	+3	—	—	-5	—	—	+10	+2	+2	+2
	3	+3	+6	+4	—	+5	-2	-1	+1	+1	—	0	0	0
	4	+6	+7	+7	+9	—	—	+3	—	—	+3	+4	+4	+1
1900 Re-s	1	+7	+7	+8	—	+1	+3	+5	+7	+5	—	+4	+6	+3
	2	-11	-20	-28	-37	—	—	-39	—	—	-31	-30	-20	+13
	3	0	-3	-7	—	-8	-15	-12	-6	-5	—	-4	-4	-2
	4	+20	+31	+40	+40	—	—	+49	—	—	+42	+38	+33	+16
925H	1	0	0	+3	—	+2	+4	+3	+6	+3	—	+1	+3	+4
	2	-1	-32	-43	-46	—	—	-45	—	—	-29	-43	-32	-21
	3	0	-3	-6	—	-11	-16	-14	-4	-4	—	-6	-6	-4
	4	+24	+37	+49	+51	—	—	+58	—	—	+42	+33	+23	+4
A8 Gaged and Free	1	-1	-3	-5	—	-6	0	+1	0	0	—	-1	-1	-1
	2	-1	-1	-2	-1	—	—	-4	—	—	-3	-4	-5	-4
	3	0	+2	+5	—	+7	+11	+11	+10	+9	—	0	+1	+1
	4	-2	-2	+1	0	—	—	-3	—	—	-2	0	0	-1
1900 Re-s	1	0	-4	-4	—	-7	-3	-5	-5	-6	—	-2	+2	+3
	2	+8	+11	+11	+7	—	—	+16	—	—	+12	+4	+4	+4
	3	0	-1	+1	—	-2	+1	+1	+4	-3	—	+6	+7	+7
	4	-2	-5	-3	-15	—	—	-18	—	—	-13	-3	-4	-4
925H	1	-2	-6	-6	—	-9	-4	-6	-5	-8	—	-5	0	+1
	2	+9	+11	+14	+12	—	—	+19	—	—	+12	+8	+5	+2
	3	+4	+4	+5	—	+4	+7	+8	+8	+3	—	+8	+12	+12
	4	-6	-6	-2	-9	—	—	-6	—	—	+9	+21	+25	+29

TABLE C-2 (CONTINUED)

CONTOUR DATA

Specimen and Condition	Face	$\frac{1}{2}$	1	$1\frac{1}{2}$	Flex $1\frac{3}{4}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4	Flex $4\frac{1}{4}$	$4\frac{1}{2}$	5	$5\frac{1}{2}$
A9	1	-2	-7	-9	—	-9	+7	+15	+14	+9	—	+9	+5	0
Gaged	2	+1	+2	+1	-2	—	—	0	—	—	-1	-1	-1	0
and	3	+4	+8	+7	—	+12	+16	+18	+13	0	—	-8	-3	-8
Free	4	-1	-1	-1	-3	—	—	-6	—	—	-4	-3	-2	-2
A10	1	-2	-2	-3	—	-6	+7	+16	+13	+11	—	+9	+6	+5
Gaged	2	0	-1	-2	-4	—	—	-5	—	—	-6	-4	-2	-2
and	3	+3	+3	+7	—	+10	+13	+18	+6	-7	—	-12	-8	-3
Free	4	0	0	-1	-1	—	—	+4	—	—	-1	-1	+1	+1

Station Number

TABLE C-3

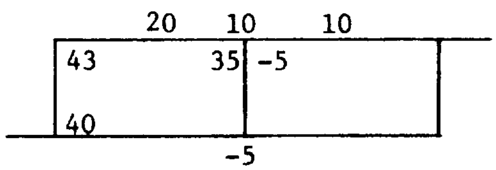
STRAIN GAGE DATA - AXIAL SPECIMENS

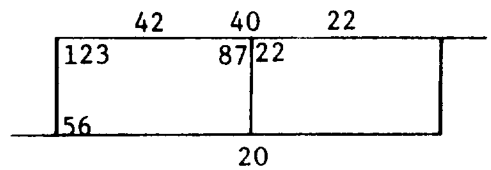
Notes: 1. See Figure 2 in the text for strain gage locations.

2. Numbers are strain in microinch per inch referred to the as-gaged condition.

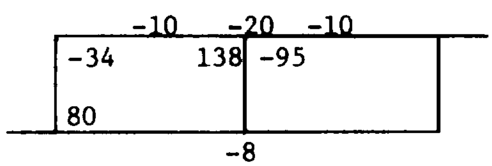
Specimen	Diagonal Slot Free	Vertical Beam Free

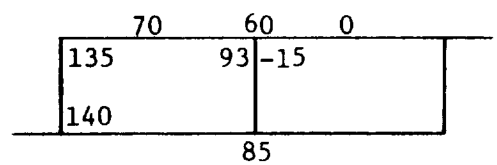
A1



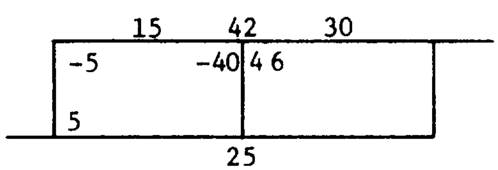


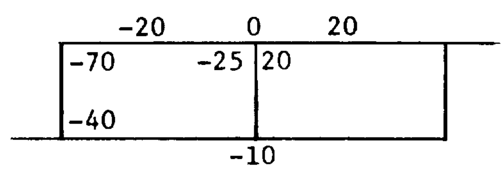
A2



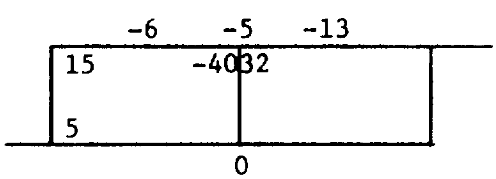


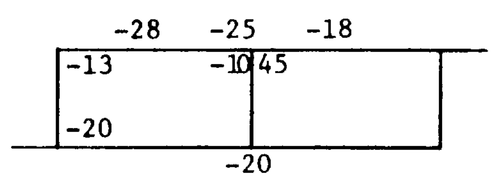
A3



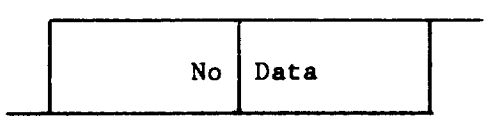


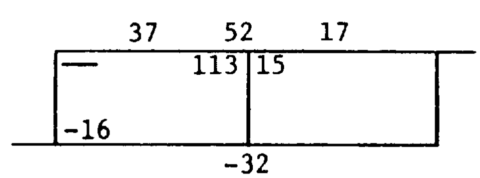
A4



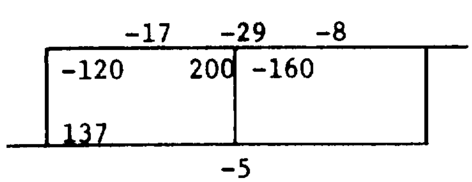


A5





A6



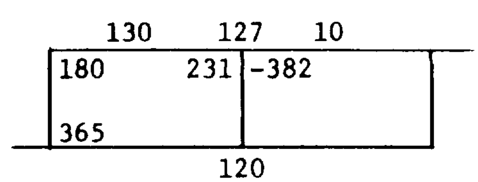


TABLE C-3 (CONTINUED)

STRAIN GAGE DATA - AXIAL SPECIMENS

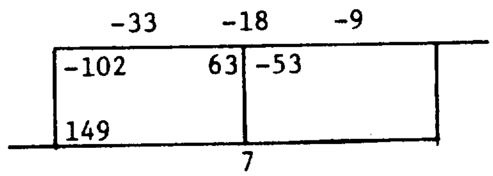
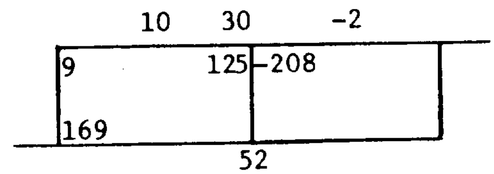
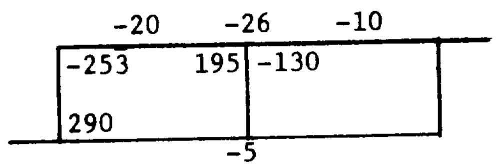
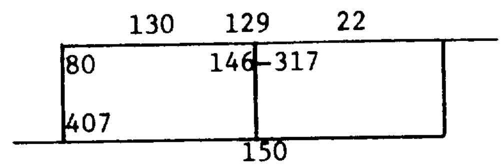
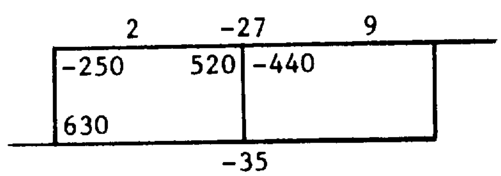
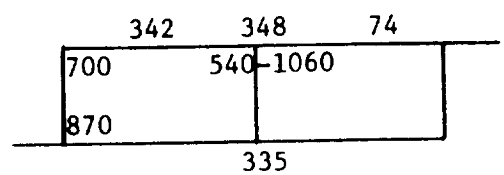
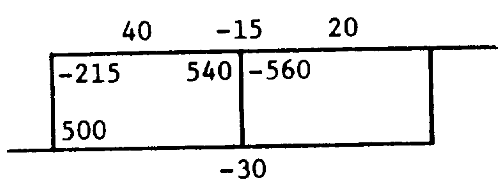
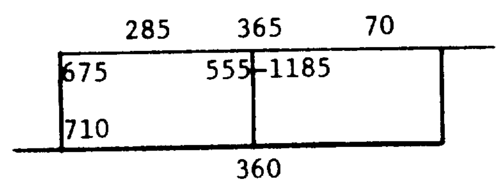
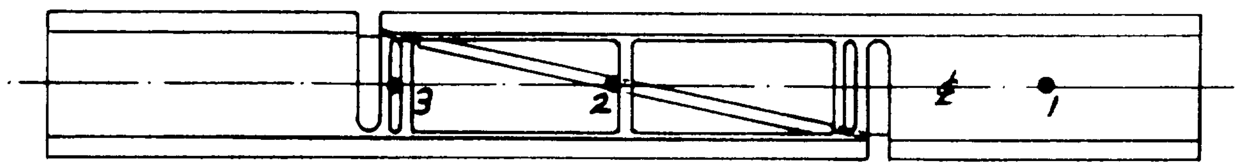
Specimen	Diagonal Slot Free	Vertical Beam Free
A7		
A8		
A9		
A10		

TABLE C4

TEMPERATURE DATA

1. Re-solution Treatment, Specimens A3, A7



Thermocouple Locations

Time	Retort	Furnace	Specimen Thermocouples A7 1	A7 2*	A3 1	A3 2	A3 3
0950	350	1100	490	520	500	520	495
1010	880	1330	1100	1100	1080	1090	1070
1030	1300	1520	1420	out	out	1420	1410
1050	1540	1640	1620	—	—	1620	1620
1110	1720	1800	1780	—	—	1775	1775
1120	1780	1830	1842	—	—	1830	out
1133	1885	1900	1900	—	—	1900	—
1150	1910	1895	1915	—	—	1918	—
1205	1865	1765	1820	—	—	1842	—
1215	1700	1540	1650	—	—	1660	—
1225	1610	1450	1540	—	—	1565	—
1245	1490	1310	1420	—	—	1430	—
1300	1350	1190	1270	—	—	1260	—
1315	1120	990	out	—	—	1120	—
1330	1100	900	—	—	—	860	—
1345	Removed from oven		—	—	—	800	—
1400			—	—	—	315	—
1415			—	—	—	190	—

* T/C #3 on A7 failed upon oven startup

TABLE C4 (CONTINUED)

TEMPERATURE DATA

2. 925H Harden - A1, A3

Time	Oven T/C	A1 1	A1 2	A1 3	A3 1	A3 2	A3 3
		Specimen Thermocouples*					
0930	on	—	—	—	—	—	—
0940	260	270	275	280	285	335	332
1000	650	680	680	680	685	685	680
1030	915	990	990	990	990	990	990
1050	920	1000	1000	1000	1000	1000	1000
1115	912	1000	1000	1000	995	995	995
1300	930	1000	1000	1000	995	995	1000
1410	932	1005	1005	1005	1000	1000	1000
1510	Off	790	785	710	640	600	640
1515	—	630	630	680	580	540	590
1516	—	590	570	610	520	500	530
1518	—	540	480	520	450	435	470
1520	—	430	410	440	380	360	390
1525	—	270	245	270	225	210	230
1535	—	172	165	170	150	148	155
1545	—	122	120	123	115	115	115

3. 925H Harden - A5, A7

Time	Oven T/C	A7 1	A7 2	A7 3	A5 1	A5 2	A5 3
		Specimen Thermocouples*					
0800	on	135	155	142	140	165	168
0810	400	400	422	400	395	410	412
0830	925	945	950	945	927	930	910
0930	930	1000	1020	1020	1010	1010	1010
1015	925	1020	1020	1020	1010	1010	1010
1115	925	1020	1020	1020	1010	1010	1020
1300	920	1000	1000	1000	1000	1000	1000
1345	Off	900	860	860	840	830	820
1346	—	895	650	720	760	720	710
1350	—	710	580	650	700	680	670
1355	—	500	460	510	480	500	530
1410	—	150	145	146	150	160	175

* T/C resistance is not matched to indicator. Oven T/C is correct.

<u>APPENDIX D</u>

<u>MACHINING DATA</u>

Table No.		Page No.

TABLE D-1

MACHINING SPECIMEN DATA

Note: 1) Refer to Figure 3 and Table IV of the text for station number and heat treatment codes.

2) Numbers in table are total indicator readings in .0001 inch and angle of maximum outward deviation.

3) Specimen quadrant code

Specimen	Quadrant Cut	Station						Cut Temp °F
		1	A		B		2	
M1	None	4	10	180°	10	180°	2	—
	1	5	8	180	7	180	3	300
	4	4	10	180	10	180	4	325
	2	5	12	180	11	180	4	350
	3	4	8	180	5	180	4	375
M2	None	3	14	120	18	120	2	—
	1	3	18	110	16	110	3	200
	2	3	17	110	13	110	3	400
	3	3	17	110	17	110	3	390
	4	3	14	110	15	110	3	400
M3	None	4	18	180	17	180	3	—
	1	4	20	180	20	180	3	270
	2	4	19	180	18	180	3	460
	3	4	18	180	17	180	3	420
	4	5	21	180	18	180	3	530
M4	None	4	3	0	4	90	4	—
	1	4	8	180	12	270	3	100
	2	4	25	180	26	170	3	150
	3	4	17	180	20	200	3	300
	4	3	4	270	6	270	3	425
M5	None	8	4	180	5	220	3	—
		8	18	180	14	180	3	300
		7	28	180	28	180	4	375
		8	18	180	19	200	3	350
		8	10	270	8	270	3	400